Managing Stormwater More Sustainably Using Green Infrastructure and Low Impact Development

by

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Ethics Statement

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Abstract

As cities continue to develop and densify, there is usually a notable increase in impermeable surface areas. With the introduction of more impermeable surfaces, significantly less rainwater is able to infiltrate back into the ground. When rainwater travels over impermeable surface areas, the runoff picks up toxic pollutants. This polluted water, hereafter referred to as "stormwater", is generally conveyed into storm networks and eventually discharged into receiving outfall areas. When large volumes of polluted stormwater are discharged at high velocities, this can result in the pollution and erosion of receiving areas. As cities continue to grow, and with climate change on the rise, sustainably managing stormwater has become increasingly more important in today's urban environment. Relying only on conventional stormwater management practices can be problematic, since today's stormwater management solutions should be designed to respond to climate change, and the changing urban landscape. Using lesson-drawing and the voluntary transfer of information from the City of Philadelphia, this thesis suggests the use of green infrastructure, and low impact development in order manage rainwater as close to the source as possible. As a guiding principle, this thesis encourages planners, engineers, civil designers, and landowners to build natural processes back into the altered urban environment and use green infrastructure and low impact development whenever possible to manage stormwater more sustainably.

Keywords: stormwater management; mimic nature in urban environments; low impact development; sustainability; runoff

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List of Acronyms

BMP	Best Management Practice
COV	City of Vancouver
DNV	District of North Vancouver
GVS&DD	Greater Vancouver Sewerage and Drainage District
HUC	Hydrological Unit Code
ILWRMP	Integrated Liquid Waste Resource Management Plan
ISMP	Integrated Stormwater Management Plan
LID	Low Impact Development
LWMP	Liquid Waste Management Plan
SWM	Stormwater Management

Chapter 1.

Introduction

Stormwater runoff is a leading contributor of pollution in rivers, streams, lakes, and oceans (Rasmussen & Schmidt, 2009, p. 1). The chemical composition of stormwater is complicated, and runoff often contains harmful chemicals and metals originating from many different sources. Sustainably managing stormwater in a city is a challenging task which requires the cooperation and understanding of governments, businesses, developers, and residents.

As many cities continue to grow, and with climate change on the rise, this thesis asks the question: how can planners, engineers, and civil designers achieve sustainable stormwater management solutions within cities? To address this research question, this thesis uses lesson-drawing from other jurisdictions, academic research, and information gathered from key informant interviews, to suggest that in addition to using conventional stormwater management strategies, green infrastructure and low impact development solutions should also be considered in order to manage runoff more sustainably. These strategies involve the planning and engineering of design solutions that are specifically built to mimic natural processes, in an effort to manage stormwater runoff close to its source, reduce runoff volume where possible, and safeguard water quality.

During the interview process, Participant 1 told me that in order to secure sustainable stormwater management solutions, municipalities should have a requirement secured within their Development Servicing Bylaw that states that planners and engineers can require green infrastructure and low impact development solutions to be implemented on all newly developed lots. In the Literature Review section of this thesis, I have developed a conceptual framework in order to determine whether lessons can be successfully drawn from the City of Philadelphia's Green Streets Design Manual. Research and key informant interviews conducted on this topic also highlight the importance of managing runoff as close to the source as possible by designing natural stormwater management features within cities that allow runoff to absorbed back into the ground.

This thesis also notes that municipalities should have information readily available on the topic of sustainable stormwater management so that landowners and developers can understand why this is important, and the rationale behind municipal requirements. This information can be included on municipal websites, and within brochures, and pamphlets at city halls. Since many of these sustainable technologies require periodic maintenance once installed in order to operate efficiently, a basic understanding of the system and its function is preferable. In general, landowners should be helped to understand why mismanaging stormwater runoff is problematic, and how pollution problems associated with this can affect our environment and our biodiversity. This is why this thesis has chosen to provide an extensive background on this topic, explaining why changes need to be made to the way professionals manage stormwater today. In addition to pollution problems associated with the chemical composition of stormwater, the total volume of runoff must also be taken into consideration, since overlooking this can cause flooding, the erosion of land in receiving outfall areas, and damage to public and private property. Mismanaged stormwater can pollute and erode creeks, streams, lakes, and oceans, and if left unchecked, this pollution can result in a loss of biodiversity within sensitive stream ecosystems.

The difference between the terms “green infrastructure”, and “low impact development” is subtle, and often relates to scale. Low impact development can be understood as a subset of practices and approaches used within green infrastructure; however, low impact development specifically relates to natural sustainable stormwater management solutions implemented at the site level. The term ‘green infrastructure’ however, describes the process of managing stormwater naturally from a larger, broader view of the community, or watershed. Recently, the distinctions between the two terms are diminishing, and people have begun to use them interchangeably regardless of scale.

The goal of this thesis is to draw lessons from municipalities such as the City of Philadelphia who have developed award winning stormwater management solutions in an effort to manage runoff more sustainably. This thesis also seeks to bridge the gap between academic research and industry practices. Information on how municipalities deal with stormwater management has been gathered through key informant interviews. The research component of this thesis includes reviewing literature on policy learning, policy transfer, and policy development. A conceptual framework developed through the review of this literature has been summarized in Section 2.5 of this thesis, and this framework has been used to determine whether lessons can be successfully drawn from one jurisdiction and utilized in another.

1.1. Urbanization, Densification and Stormwater Management

Urbanization and land development can have significant adverse impacts on stormwater management, especially if the developed land has been converted from woods, meadows, or other natural conditions to highly disturbed areas with large percentages of impervious and non-native vegetative cover. Generally in natural undeveloped areas, a small percentage of total rainfall converts to runoff because precipitation is able to infiltrate back into the ground through permeable surfaces such as soil, grass, and other vegetation.

In cities however, planners and civil engineers have reconfigured the natural landscape in an effort to add density, mobility, and connectivity. Natural areas are often repurposed to accommodate additional growth in many cities, and with rapid urban growth, the expansion of impervious land is almost inevitable (Sohn et al., 2017, p. 1886). As the population in the Vancouver region continues to rise, and as the demand for land continues to increase, many municipalities in the Lower Mainland including the District of North Vancouver have noticed building footprints becoming larger. At the DNV, planners, and plan reviewers have noticed a trend where older, modestly sized single-family homes are being demolished and replaced with significantly larger structures. After speaking with other municipal planners and colleagues in the Lower Mainland, I was told that this trend in densification is generally consistent. In many busy, growing cities, roads often need to be built further and wider to connect people with one another, and parkades often need to be constructed deeper in order to accommodate more vehicles. At the DNV, planners and engineers routinely receive development applications that propose deep excavations for basements and parkades, which can be problematic since this can disrupt natural water tables and can compromise and disturb the water balance in an area. Introducing large areas of impermeable surface such as roofs, roads, and parking lots can increase the production of stormwater runoff because rainwater that was once able to infiltrate into the ground, now is unable to do so. Water generally takes the path of least resistance, and when clean rainwater is carried over impermeable surfaces, it picks up pollutants before it is eventually discharged into outfall areas (Walsh et al., 2012, p. 2).

When natural environments have been changed or modified, careful consideration needs to be given to managing the increased production of runoff. If ignored, stormwater runoff can overwhelm municipal storm networks, and this can result in flooding, erosion, pollution, and property damage that can threaten private property, public property, infrastructure, roads, and even sanitation systems.

The suspended sediments, chemicals, and metals in stormwater runoff can pollute downstream rivers, streams, and other receiving bodies of water if managed improperly. To address this issue, this thesis encourages planners, engineers, and designers to mimic natural processes in urban environments where possible, and use low impact development, and green infrastructure strategies to sustainably manage stormwater. Examples of this could include bioretention ponds, constructed stormwater wetland areas, bioswales, permeable pavement, and other low impact development strategies which not only serve a technical purpose by mitigating problems downstream, but can also be aesthetically appealing. As we seek to mitigate the problems associated with improperly managed stormwater, these strategies can be useful, low cost solutions that replicate natural systems.

1.2. What is a Watershed?

A watershed is an area of land where surface water drains to a single destination such as a stream, lake, or ocean. Watersheds are also called drainage basins because they collect all the water that is not evaporated or transpired. Sources of water include rain, snow, and ice melt. It is a misconception to assume that only waterbodies such as rivers, lakes, and wetlands are part of a watershed. Rather, any land such as parks, industrial areas, forests, parking lots, and even the soil that structures are built on should be included in the definition of a watershed. The simplest and easiest way to think about a watershed is as a funnel that collects all the water within a specific area and then drains it into the nearest body of water. Water is usually channeled into soil, groundwater, creeks, and streams while making its way to larger rivers, and eventually to the ocean. Every individual in a city lives within a watershed, and practically speaking, watersheds know no political boundaries, whether they are local, national, or international. Everything from the environment, to the economy, to our society all depends on securing, protecting, and maintaining the health of our watersheds.

The area of a watershed is typically defined by topography. The borders of a watershed are defined by a drainage divide, which can be explained as the highest ridge that divides the water from falling into its own basin, rather than into a different basin. The area of a watershed is also defined by what common source of water it flows into. For example, most individuals live in watersheds that flow into nearby streams, or creeks. These watersheds in turn comprise parts of larger watersheds that drain into rivers, lakes, and ultimately to the ocean. At a macro level, all land in North America lying to the west of the Continental Divide in the Rocky Mountains drains through a series of watersheds into the Pacific Ocean.

Hydrologists use hydrological unit codes (HUCs) in order to classify watersheds. It is important for watershed managers to be able to predict how much precipitation to expect within a specific watershed. Precipitation measurements across different watersheds are important because they allow watershed managers to estimate and calculate how much water and runoff to ultimately expect in their basin.

When planners and engineers assess a site, there are several factors that must be accounted for when predicting runoff volume. Even infiltration of water back into the ground often depends on several factors, the most basic of which includes the availability of permeable surface in an area, the type of soil that exists an area, the absorbency of the soil, and the current state of soil saturation at any given point in time. Other factors to consider include the amount of plant life and vegetation that exists in the area, and the rate at which these plants utilize water. Calculations also depend on temperature, or atmospheric conditions since these factors can influence the rate of evaporation. Finally, watershed managers should also take into account how much water is stored and used by people in cities, or for agricultural uses.

After compiling all the information above, hydrologists produce a hydrograph which shows the past, current, and predicted levels of streams and rivers. Considering all the information required to produce a hydrograph, it becomes easy to appreciate the complexity of determining the amount of water in a watershed that is expected to flow downstream after a rain or storm event.

Managing water resources appropriately is important, since clean rainwater is usually considered to be a precious and renewable resource that is vital for human survival (Bredemeier, 2011, p. 10). Drinking water, also known as potable water, is water that is safe for human consumption. Typical uses for potable water include: drinking, cooking, food preparation, showering, toilet flushing, and agricultural irrigation. The conservation of clean water is important, and in many cities, there are competing thoughts on whether potable water, or reclaimed water should be used for certain activities such as flushing toilets, and irrigating lawns.

1.3. Metro Vancouver's View on Stormwater Management

In 2001, Metro Vancouver and its associated members created and adopted the Liquid Waste Management Plan (LWMP) which endorsed the view that stormwater is a resource, and if managed properly, could be used to protect and enhance a watershed's health (Urban Systems, 2012, p. 2). The Liquid Waste Management Plan set an approach forward to integrate stormwater management planning that focuses on incorporating the environment, drainage, and land use planning within a watershed in an effort to address the potential stormwater impacts on communities. By 2014, Metro Vancouver's member municipalities committed to undertake Integrated Stormwater Management Plans (ISMPs) for all semi-urban and urban watersheds.

In 2010 a new Integrated Liquid Waste and Resource Management Plan (ILWRMP) was created and adopted, which reaffirmed the commitments that member municipalities made to undertake ISMPs by 2014, and also required municipalities to implement these plans (Urban Systems, 2012, p. 2). Metro Vancouver has taken a strong stance on stormwater management, and views this as a regional issue that must be sustainably addressed by all municipalities through the use of ISMPs. ISMPs can be understood as technical documents that are created using comprehensive studies that examine the linkages between land use planning, drainage servicing, and overall environmental protection.

The purpose of an ISMP is to support the growth of an urban community in a sustainable and responsible way that maintains or possibly improves the overall health of a watershed. If implemented correctly, integrated stormwater management plans can be powerful tools that can help municipalities set clear watershed management direction within their communities.

Metro Vancouver has noted that in response to commitments made under the 2001 Liquid Waste Management Plan (LWMP), most member municipalities have initiated or completed ISMPs for watersheds in their communities. The District of North Vancouver is currently working on completing their ISMP for the municipality by the end of the 2020 calendar year. The District's ISMP is primarily focused on securing small scale infiltration on-site and off-site through the use of green infrastructure and low impact development. The District's ISMP also includes a Water Balance Model, which is an online tool designed to provide information to landowners on sustainable stormwater management practices within their lots. The Water Balance Model is discussed in detail within Section 5.1.4 of this thesis.

By reflecting on completed integrated storm water management plans, both Metro Vancouver and other municipalities can review the successes and challenges associated with ISMP development and implementation. Metro Vancouver is currently in the process of studying local municipalities and their adopted ISMPs in a hope that sharing this information will help provide guidance and support to all local governments that are currently still working on completing any remaining ISMPs.

From a governance perspective, it is important to understand the everyday roles that Metro Vancouver and their municipal members play in stormwater management. Municipalities are responsible for operating and maintaining the collector storm sewer infrastructure that conveys stormwater to the nearest waterway. These responsibilities include ensuring that current regulations are met, ensuring that actions set in the regional liquid waste management plan are followed, cleaning of storm drains, and education programs. Metro Vancouver however, is responsible for providing policy guidance and coordination through committees such as the Stormwater Interagency Liaison Group (SILG), which allows municipalities to share experience, knowledge, and provides guidance on stormwater management practices. Metro Vancouver and the Greater Vancouver Sewerage and Drainage District (GVS&DD) are also responsible for owning, operating, and maintaining regional trunk sewers and major wastewater treatment plants.

In an effort to educate residents on the importance of stormwater management, Metro Vancouver has developed a Homeowner's Guide to Stormwater Management, which they encourage local governments to modify and distribute within their communities. On private property, this guide encourages landowners to reduce impermeable surfaces where possible and include raingardens, sumps, rockpits, infiltration trenches, absorbent landscaping, disconnected roof leaders, detention tanks, and permeable 'country lane' style driveways. Metro Vancouver's guide also suggests the use of permeable materials such as grass pavers, gravel, porous concrete or porous asphalt to allow water to infiltrate back into the ground (Metro Vancouver, 2019a). Many of the sustainable stormwater management solutions noted in this guide such as permeable pavement, 'country lane' designs, absorbent landscaping, detention tanks, grass pavers and rain gardens are detailed, described, and discussed within Chapter 4 of this thesis.

Metro Vancouver also reminds homeowners that everything poured into a storm drain makes its way directly to the nearest body of water, and substances such as motor oils, antifreeze, solvents, paints and other household chemicals need to be disposed of appropriately (Metro Vancouver, 2019b). With regard to car washing, commercial car washes are suggested to be used rather than washing cars at home, since the chemicals cleansers used at these locations are collected and channelled into the sanitary sewer, rather than the storm sewer system.

1.3.1. The Integrated Liquid Waste & Resource Management Plan (ILWRMP)

Within Metro Vancouver's Integrated Liquid Waste Resource Management Plan (ILWRMP), the term 'liquid waste' consists of wastewater that has been collected from businesses, houses, institutions, and industries around the region, as well as stormwater runoff. Given this broad definition, this thesis reinforces that liquid waste needs to be managed sustainably, appropriately, and responsibly, rather than being channelled into pipes and discharged into receiving environments untreated.

Traditionally, liquid waste has been viewed as a pollutant or as an unusable product that needs to be treated or disposed of however, Metro Vancouver's ILWRMP suggests that stormwater can also be an asset in the natural environment in the form of creeks and other watercourses (Metro Vancouver, 2010, p. 5). As a senior governing body, Metro Vancouver understands that as water resources become scarcer worldwide, liquid waste is increasingly being recognized as a resource through which water, energy and nutrients can be extracted and reused again sustainably.

The long-term vision for liquid waste management is to ensure that all elements of liquid waste within the region will be efficiently recovered as energy, water, nutrients, or other usable materials, or otherwise retuned to the natural environment as part of the hydrological cycle in a way that protects our environment and our public health (Metro Vancouver, 2010, p. 5). In order to achieve this vision, Metro Vancouver's ILWRMP sets three goals. The first goal is to protect public health and the environment by managing sanitary sewage and stormwater at their sources, and providing wastewater collection and treatment services which protect the natural environment. Metro Vancouver's goal of treating stormwater as close to the source as possible, is an idea that this thesis will continue to promote through the use of both green infrastructure and low impact development. This is why the District of North Vancouver's ISMP, which is still being developed, promotes small scale on-site infiltration, in an effort to manage stormwater onsite at the source, rather than directing the flow into the storm sewer network.

The second goal within this plan is focused around using liquid waste as a resource. This is primarily achieved using wastewater treatment plants which can allow energy to be recovered from the heat in the sewage, and from biogas which is generated by the wastewater treatment process. Participant 1 and I discussed that this heat can be conveyed and used by buildings, but only if they are built hydronic ready. This is why the Development Planning Department at the District of North Vancouver generally requires new buildings to be hydronic ready so that they could benefit from this energy recovery mechanism. In addition to heat recovery, and cleansing water, wastewater treatment plants are also able to recover minerals from polluted sewage.

The final goal within the ILWRMP is to ensure effective, affordable and collaborative management, which Metro Vancouver strives to achieve by maintaining, monitoring, and investing resources into liquid waste infrastructure. Metro Vancouver is also committed to ensuring that a regional management system will be pursued, and they do this through the requirement of integrated stormwater management plans.

1.3.2. District of North Vancouver's Integrated Stormwater Management Plan (ISMP)

As stated earlier in this thesis, the District of North Vancouver is currently working on completing their integrated stormwater management plan (ISMP). During the interview process, participant 5 told me that the District's ISMP is focused on balancing land use development with environmental concerns, and once complete, it will be used to guide how stormwater is managed within the municipality. This is consistent with the goals and objectives outlined by Metro Vancouver though the Liquid Waste Management Plan, and the Integrated Liquid Waste Resource Management Plan.

The environmental objectives of the District's ISMP are focused on maximizing base flows, maximizing fish populations, and maximising riparian ecosystems. The municipality seeks to maximize base flows by protecting natural environments, and reducing the negative impacts of land use changes by infiltrating rainwater back into the ground to mimic the natural water balance (District of North Vancouver, 2019). Fish populations are protected by ensuring that watercourses provide clean water, food, habitats, and suitable flows required for aquatic life. Riparian ecosystems are maximized by planting native vegetation (including trees), and removing invasive species (District of North Vancouver, 2019).

From a stormwater management perspective, participant 5 and I discussed that the District's ISMP focuses on primarily managing both rainwater and stormwater as close to the source as possible predominantly by using low impact development strategies. This approach to stormwater management is also consistent with what is outlined in Metro Vancouver's Homeowner's Guide to Stormwater Management. The main idea is to get water to infiltrate back into the ground, similar to what would occur if rain fell on the earth's natural, undeveloped, permeable surface. Participant 5 and I discussed that managing runoff in this way is preferable to directing all stormwater into sewers, because this strategy seeks to maximize the amount of rainwater that is able to infiltrate back into the ground before it can travel over land and pick up toxic pollutants.

Although the District's ISMP has not been finalized yet, participant 1 and I discussed that ISMP best practices are already being incorporated into capital projects and District operation programs. For example, on the District's new Keith Road bridge project, the traditional approach of collecting stormwater in pipes and discharging into nearby creeks and streams was replaced with a more sustainable stormwater management approach. In an effort to simulate natural watershed conditions, municipal staff have included bioswales and other green infrastructure solutions such as flat curbs and dispersion drains to capture, detain, and infiltrate rainwater back into the ground. Flat curbs, which allow water to runoff into natural surfaces were also used in the District's new parking lot at Bridgeman Park (District of North Vancouver, 2019). Participant 1 and I also discussed the importance of replanting, since vegetation in riparian zones can help fish populations by providing shade, keeping water cool, facilitating habitats, and providing erosion protection by way of their root structures. For the Keith Road bridge project, the District of North Vancouver planted more than 465 trees and 19,000 shrubs in an effort to restore the riparian habitat (District of North Vancouver, 2019).

In addition to the project specific ISMP best practice initiatives incorporated above, the District of North Vancouver also conducts frequent inspections of their greenbelts and riparian corridors. During these inspections, staff from the District's Environment Department are responsible to monitor water quality, and sample fish presence. The data gathered from these inspections are generally used to assess watershed health and help guide future discussions for land use and capital projects in the area.

1.3.3. District of North Vancouver's 2017 ISMP Council Workshop

On June 20, 2017, in a council workshop meeting, The District of North Vancouver's Deputy General Manager of Engineering brought forward the municipality's ISMP framework to council for consideration and prioritization (The District of North Vancouver, 2017a, p. 4). Council was informed that the ISMP document was a component of the municipality's Climate Change Adaptation Strategy, and that the final adoption of this document would allow different departments that have an impact on drainage to work together to sustainably manage stormwater. The departments within this category would include the Building, Planning, Engineering, Utilities, Parks, and Public Works Departments.

Council was informed that the overall goal of the ISMP is to provide solutions that improve watershed health by directly addressing the impacts of stormwater drainage from properties and streets into creeks and other receiving areas. During the interview process, participant 1 informed me that within the District, this is primarily achieved through small scale on-site infiltration.

The Project Engineer responsible for working on the ISMP presented the framework to council which can be understood as follows: identify values and challenges (this includes seeking input from residents and stakeholders such as the North Shore Stream-keepers), define objectives and measures, develop and evaluate alternatives, implement plans, and monitor implementation. After this brief overview of the framework, the District's Project Engineer explained the importance of release rates on watershed health, telling council that redevelopment creates non-porous surfaces, resulting in higher peak flows during storm events (The District of North Vancouver, 2017a, p. 5).

The idea that redevelopment, if left unchecked, generally replaces permeable surfaces with impermeable was discussed in Section 1.1 of this thesis, and in order to manage this trend, this thesis will detail several low impact development, and green infrastructure solutions that promote the infiltration of water back into the ground before it is able to runoff and pick up toxic pollutants. The solutions that will be presented in Chapter 4 of this thesis are consistent with the District of North Vancouver's ISMP goal and environmental objectives, and Metro Vancouver's goals of managing stormwater sustainably and reducing peak flows.

Once District staff had concluded presenting, council began their discussion, and the following noteworthy comments were made. Some councillors commented on the visible impacts such as pollution and erosion that construction had on small creeks and larger watersheds. They noted that certain watersheds such as the 'Hastings Creek' watershed were more sensitive than others and may require immediate attention. Council concurred with staff suggesting that they too have noticed a problematic trend where permeable surfaces are being covered with impermeable paving materials rather than grass, and vegetation. Finally, council inquired what staff could reasonably require from developers and homeowners under current regulations.

1.4. The World Health Organization’s View on Managing Water Resources Appropriately, and The Importance of Providing Safe Potable Water Globally

The World Health Organization has also taken a strong stance on water management, and states that better management of water resources can boost a countries’ economic growth and contribute greatly to poverty reduction. As urban environments continue to undergo land use changes, this thesis promotes the use of green infrastructure and low impact development as a strategy to help manage stormwater sustainably and safeguard potable water usage within a city. In 2010, the United Nation’s General Assembly explicitly recognized the human right to safe water and sanitation, stating that, “Everyone has the right to sufficient, continuous, safe, acceptable, physically accessible, and affordable water for personal and domestic use” (World Health Organization, 2019).

Rapid population growth has increased the demand for potable water tremendously, and there is a growing concern in the world today regarding the scarcity of clean water resources (Antunes et al., 2016, p. 1). Recognizing the trajectory of global population growth, many researchers suggest that potable water should be used sparingly, since this is necessary for the conservation of this precious resource (Antunes et al., 2016, p. 1). This thesis recognizes the importance of conserving potable water and reinforces that cities should make every effort to manage stormwater, and clean water resources more sustainably. Additionally, this research also promotes limiting the use of potable water where appropriate for specific activities such as flushing toilets.

In 2017, the World Health Organization reported that only 71% of the global population had access to a safely managed drinking water service that was located on their premises, with potable water free of contamination and available when needed. 90% of the global population used at least a basic water service, which is defined as an improved drinking water source that is accessible within a round trip of 30 minutes to collect water (World Health Organization, 2019). Unfortunately, globally approximately 780 million people lack access to a basic improved drinking water source (Centre of Disease Control and Prevention, 2018). The term improved water source refers to a type of water source protected from outside contamination through human intervention. Some examples of improved drinking water sources can include protected wells, public standpipes, a piped household water service connection, and protected springs.

The World Health Organization estimates that contaminated drinking water is responsible for the deaths of approximately 485,000 people each year, and the cause of death is most commonly reported to be diarrhoeal (World Health Organization, 2019). Diarrhea is the most widely known disease linked to contaminated water, and although diarrhea is largely preventable, in 2017 it was responsible for the deaths of approximately 297,000 children aged 5 years and under (World Health Organization, 2019). Unsafe drinking water, accompanied with the inadequate availability of water for basic hygiene, and lack of access to sanitation all contribute to approximately 88% of deaths from diarrheal diseases (Centre of Disease Control and Prevention, 2018). With young children particularly at risk from contaminated water related diseases, managing water systems appropriately, and providing access to clean potable water can result in better health for children, which in turn can play a role in better school attendance, ultimately resulting in potential positive long-term consequences in their lives. Unfortunately, in countries where clean water is scarce and not readily available, handwashing and other basic sanitary measures are usually not prioritized, and this can increase the likelihood of diarrhoea and other preventable diseases.

Unfortunately, even in countries like the United States, a vast majority of waterborne diseases go unreported because of difficulties diagnosing the specific cause of the illness (Centre of Disease Control and Prevention, 2018). For example, in the United States, approximately 99 million people suffer with acute gastrointestinal illnesses each year, and studies estimate that approximately 6% to 40% of these illnesses could be caused by drinking contaminated water (Gaffield et al., 2003, p. 2). More specifically, exposure to Cryptosporidium is fairly common in the US, and approximately 17% to 32% of people tested are found to have evidence of infection by young adulthood (Gaffield et al., 2003, p. 2). Cryptosporidium are parasitic alveolates that can cause respiratory and gastrointestinal illnesses that cause symptoms of diarrhea, which are sometimes accompanied with a persistent cough.

In many parts of the world, insects such as mosquitos live and breed in stagnant water. These bugs can carry and transmit diseases such as malaria, and dengue fever for example. This is another reason why it is important to manage precipitation appropriately, and design urban areas to mitigate any standing or pooling water.

By 2025, it is estimated that approximately half of the world's population will be living in water stressed areas, and in some of the least developed countries around the world, approximately 22% of health care facilities have no water service, 21% have no sanitation service, and 22% do not have access to a waste management service (World Health Organization, 2019).

Fortunately, in developed cities like Vancouver, clean potable water is generally readily available; however, this precious resource must be protected and used appropriately and sustainably. Inadequate, or inappropriately managed water and sanitation services can expose individuals to preventable health risks. Improperly managing urban, industrial, or agricultural wastewater can pollute and contaminate the drinking water of hundreds of millions of people by causing clean water resources to become dangerously contaminated, or chemically polluted (World Health Organization, 2019).

Studies conducted in the United States suggest that waterborne disease outbreaks can be linked to stormwater runoff, and in the US, more than half of the documented waterborne disease outbreaks since 1948 have followed extreme rain events (Gaffield et al., 2003, p. 3). Planners and engineers managing development applications are often concerned about urban and suburban parking lots, streets, and lawns because these areas can generate large loads of bacteria in stormwater. Storm mains, pipelines, and channels can also accumulate with sediment which generally blocks sunlight, inhibiting bacteria die-off and creating bacterial reservoirs (Gaffield et al., 2003, p. 3).

Climate change, population growth, increasing clean water scarcity, and urbanization can pose challenges for water supply systems. The World Health Organization encourages the re-use of reclaimed water when appropriate (World Health Organization, 2019). In recent years, more countries are employing the strategy of reusing reclaimed water for irrigation purposes, and this is especially true in developing countries. It should be noted, that if managed inappropriately, re-using reclaimed water can also pose public health risks.

As research continues in this field, options for water sources used for drinking water and irrigation purposes continue to evolve, with an increased reliance on groundwater and reclaimed water. The World Health Organization speculates that climate change will lead to greater fluctuations in harvested rainwater, and management of all water resources will need to be improved to ensure provision and quality.

1.5. The Earth's Water Cycle – Precipitation Rate Fluctuations and Stormwater Runoff

It is important to understand the earth's water cycle for the purpose of this research. Precipitation is a vital component of how water moves through the earth's water cycle, and it connects the ocean, the atmosphere, and the land. Predicting where rainfall occurs, and how much rain is expected to fall in an area allows watershed mangers to better understand precipitation impacts on streams, rivers, surface runoff, and groundwater (USGS Science for a Changing World, 2019). Scientists and watershed managers collect information on precipitation, and frequent detailed measures can help scientists determine changes in the earth's water cycle.

The water cycle describes how water evaporates from the earth's surface, rises into the earth's atmosphere before it eventually cools down and condenses into rain or snow clouds, before falling back onto the earth's surface again as precipitation replenishing our lakes, reservoirs, rivers, streams, and underground aquifers (USGS Science for a Changing World, 2019). In natural, rural areas, rainfall generally collects in lakes, rivers, soils, porous rock, and a significant amount of it flows back into the ocean, before the cycle repeats itself again. Natural forested lands and ecosystems can also supply high quality drinking water for human populations, and these natural, undisturbed areas can also safeguard against both flooding and erosion problems by retaining water through infiltration, thereby delaying and mitigating peak flows (Bredemeier, 2011, p. 10). Unfortunately, in highly urbanized areas, this protective function of forests to safeguard water quality and mitigate flooding is potentially at risk due to a changing climate, and constant land use changes (Bredemeier, 2011, p. 10).

Precipitation levels vary significantly in different parts of the world, and some areas of land receive a lot more rainfall than others. For example in certain deserts, precipitation levels have been recorded to be as low as 0.1 inches per year, yet in other tropical areas, annual reports have shown more than 900 inches of precipitation recorded (USGS Science for a Changing World, 2019). One of the driest areas in the world is located in Iquique, Chile, and records indicate that this city did not receive any rainfall in 14 years. In contrast, rain gauges in Mount Waialeale, Hawaii, have reported an average rainfall of more than 451 inches per year, and Cherrapunji, India holds the record for most rainfall in a single year, where precipitation levels were measured to be 905 inches in 1861 (USGS Science for a Changing World, 2019).

In Canada, Metro Vancouver's 2018 Climate Change Impacts on Precipitation and Stormwater Management report stated that the total annual precipitation in the region is expected to rise by 5% by the 2050s, and by as much as 11% by the 2080s (Greater Vancouver Sewerage and Drainage District, 2018, p. 18). In the United States of America, the conterminous 48 "lower" states annually receive enough precipitation per year to cover the area to a depth of approximately 30 inches. This equates to approximately 1,430 cubic miles of water each year (USGS Science for a Changing World, 2019). This enormous volume of water needs to be managed sustainably, and careful consideration needs to be given to what stormwater management treatments are in place when rainfall hits the ground. The most basic factors that need to be considered include, the intensity, duration and frequency of rainfall, the topography and grade of the land, the soil conditions in the area, the density of the existing vegetation, the temperature conditions, and the amount of impermeable surface that exists in the area.

1.5.1. Urbanization, Disruption of the Natural Environment, and Stormwater Runoff

In urbanized areas, the direct runoff volume from a rainfall event is usually relatively high because urbanization generally disrupts the natural environment (USGS Science for a Changing World, 2019). In an effort to densify our cities, planners and civil engineers have introduced buildings and other impermeable pavement surfaces that are incapable of infiltrating rainwater. In addition to this, we have designed our roads and lanes as flood corridors that channel all runoff into catch basins and drains before ultimately discharging this polluted stormwater at high volumes into streams, lakes, inlets, and other open bodies of water. By contrast, in natural or undeveloped areas, we generally notice considerably more permeable surface area, and as a result, more rainwater is often able to infiltrate into the ground and direct runoff is notably less

(Bredemeier, 2011, p. 11). For example, in developed countries like the United States, approximately 70% of the annual precipitation returns to the atmosphere by way of evaporation from land, various bodies of water, and by transpiration from vegetation, whereas the remaining 30% of precipitation is carried to lakes, streams, and oceans by overland runoff and by moving through the ground (USGS Science for a Changing World, 2019).

The majority of the rainwater that infiltrates into the ground filters its way down into subsurface aquifers before eventually making its way to lakes, rivers, streams and other receiving bodies of water. This is problematic because the volume of precipitation that reaches the streams produces an average annual streamflow in the United States of approximately 1,200 billion gallons a day. To put this into scale, in the year 2010 it was reported that the Nation’s homes, factories, and farms used approximately 355 billion gallons a day (USGS Science for a Changing World, 2019). When considering the information above, it is important for watershed managers to understand how much rainwater a city could theoretically receive during a given year, so that creative solutions can be designed in order to collect and store the rainwater for sustainable uses such as flushing toilets and possibly even irrigating lawns.

As stated earlier, in agricultural and natural lands, rainwater is generally seen as a resource; however, in cities rainwater needs to be carefully managed. During a rainfall event in urbanized areas, usually a portion of the precipitation is soaked up by plants and vegetation, some of it infiltrates back into the ground through permeable surfaces, and the remainder of the water flows over land picking up pollutants (Eckart et al., 2017, p. 414). This polluted water is then channelled by curbs, gutters, and roadways and discharged into the nearest catch basin, drain, ditch, or creek.

In most cities, civil engineers, planners, and designers have paved over permeable surfaces in order to build transportation systems, parking lots, roads, lanes, and sidewalks. As cities densify and the demand for housing and services increases, we generally lose even more permeable surface. When a site redevelops, the densification often results in a significant decrease in the site’s permeability. In addition to this, planners and engineers often remove significant amounts of trees and vegetation to accommodate these structures and transportation systems, and as a result, the natural land that was once able to absorb rainfall is now unable to do so.

In urbanized areas the percentage of precipitation that becomes stormwater runoff is much larger than in non-urbanized areas (Rasmussen & Schmidt, 2009, p. 1), and when pollution originates over a large land area without a single point of origin, this is called non-point pollution (Rasmussen & Schmidt, 2009, p. 1). By contrast, point sources of pollution originate from an identifiable single point such as a discharge pipe (Rasmussen & Schmidt, 2009, p. 1). If managed inappropriately, polluted stormwater runoff can be harmful to plants, animals, people, and biodiversity. Studies have stated that once more than 10% of a watershed becomes impervious, the discharge of stormwater runoff quickly increases, and downstream waterbodies generally struggle to maintain their natural quality (Sohn et al., 2017, p. 1871).

In a natural environment, forests, pastures and other permeable surface areas act as natural sponges that soak up rain and melting snow. Clean rainwater becomes stormwater when it falls on paved surfaces and carries away with it surface pollutants such as oil, pesticides, chemicals, and fertilizers. If left unchecked, this polluted runoff can significantly impact the water quality of creeks, streams, and sensitive watersheds.

1.5.2. What Happens to Improperly Managed Stormwater?

Unlike sanitary sewage, the stormwater that is directed into storm drains generally does not flow through a waste-water treatment facility. Instead, untreated polluted runoff is usually carried through a network of pipes, and culverts before it is ultimately flushed into streams and waterways, carrying with it harmful contaminants which can cause serious harm to fish and other aquatic life (District of North Vancouver, 2019).

In addition to polluting the natural environment, when stormwater is managed improperly, heavy runoff from large storm events can significantly erode streams and creek banks, filling up salmon spawning beds with sediment, and often destroying riparian vegetation that help keep water cold and healthy for fish and marine life (District of North Vancouver, 2019). The sustainable management of stormwater is an important issue that has long-term environmental consequences for future generations, salmon populations, and aquatic life if managed improperly today.

1.5.3. Managing Stormwater Appropriately to Safeguard Salmon Health

In urbanized areas, stormwater runoff can pose a serious threat to water quality, aquatic life, and salmon health if left unchecked (Ecological Society of America, 2015, p. 72). Many studies have been conducted on stormwater and the harmful effects that this toxic pollutant can have on salmon populations. Watersheds that have been impacted by land use activities seem to have the most detrimental impacts on salmon health, and in highly urbanized areas, it has become increasingly evident that toxic stormwater runoff is causing the premature mortality of freshwater salmon (McIntyre et al., 2018, p. 196).

As planners and civil engineers continue to alter the natural environment, safeguarding salmon populations by sustainably managing stormwater should be prioritized. Typical symptoms that salmon exhibit when exposed to and poisoned by stormwater include: a loss of orientation, surface swimming, gaping, and a loss of equilibrium, which is usually followed shortly after by death (McLellan et al., 2007, p. 196). A significant amount of research has been conducted in the Puget Sound area in Washington, since the Coho salmon population have currently been listed as a species of concern under the U.S. Endangered Species Act (McLellan et al., 2007, p. 196). It is important to understand that the Puget Sound Basin had undergone extensive growth, development, and land use changes in order to accommodate the additional population growth in the area.

Protecting salmon populations from the harmful effects of stormwater does not need to be overly complicated or cost prohibitive. Studies have shown that small-scale engineered systems that filter runoff through basic soil mixtures can remove many lethal chemicals usually found in stormwater runoff (Ecological Society of America, 2015, p. 72). It is estimated that approximately 6.3 million kilograms of oil, heavy metals, pesticides, and other toxins enter Washington State’s Puget Sound area annually, and in response to this, regional scientists and planners have engineered “bioretention” technologies such as permeable pavements, green roofs, and other surfaces capable of infiltrating water back into the ground, and mimicking the filtration ability of natural undeveloped lands in an effort to reduce the toxic runoff (Ecological Society of America, 2015, p. 72).

Certification programs such as Salmon Safe BC have been introduced to showcase sustainable development practices that protect and safeguard the health of salmon populations. Recently at the District of North Vancouver, webinars were scheduled to educate planners, engineers, and other relevant municipal staff on the importance of these certification programs and their ability to possibly encourage more sustainable development practices that prioritize green infrastructure, and low impact development practices.

1.6. Salmon Safe BC – Improper Stormwater Management and Salmon Health

Salmon Safe is a third party certification program that was founded in 1997 by the Oregon-based Pacific Rivers Council (*Salmon Safe - Urban Site Certification Program*, 2017). This non-profit accreditation program is aimed at enhancing and maintaining salmon habitat in the Pacific Northwest. This program was designed to recognize and reward responsible, ecologically friendly development management practices that protect the Pacific salmon habitat and enhance the water quality on urban sites. Salmon Safe provides a market-based mechanism that allows landowners to obtain an independent certificate of endorsement for their development, as long as the development practices used considers sustainable stormwater management solutions.

Since the program's inception in 1997, Salmon Safe has become a leading regional eco-label with more than 95,000 acres of farm and urban land already certified across the Pacific Northwest (*Salmon Safe - Urban Site Certification Program*, 2017). In an effort to promote the program, the Salmon Safe retail campaign was featured in over 300 supermarkets and food stores.

In 2010 the Pacific Salmon Foundation and the Fraser Basin Council started working in partnership with Salmon Safe U.S to bring this program to British Columbia. Nine years later, over 10,000 acres of agricultural land in British Columbia was certified as Salmon Safe. In 2013, Salmon Safe B.C launched Salmon Safe Communities to recognize and certify urban properties and promote the protection of Pacific salmon within the urban landscape (*Salmon Safe - Urban Site Certification Program*, 2017). This instance of adoption of a programme from a foreign jurisdiction demonstrates a form of policy learning and transfer, a topic which is discussed in further detail in the Literature

Review of this thesis. This thesis aims to use the policy transfer literature outlined in Chapter 2 to examine when lesson-drawing can be achieved successfully and whether a policy or programme that has been successful in one jurisdiction can be transferred to another.

The sustainable management of agricultural land was originally a key focus for Salmon Safe, although the program now also focuses their attention, and extends their certification to newly built or renovated urban sites such as offices, parks, and institutions. When the program began 10 years ago, there were over 200 American vineyards, and 300 farms that were certified as Salmon Safe (Fraser Basin Council, 2019). In British Columbia, the Salmon Safe program was introduced in 2011, and shortly after this time 22 ranches and farms in B.C. were certified as Salmon Safe. A few years later, as the program became more widely recognized, Salmon Safe increased the count to 45 certified ranches and farms by the end of 2014 (Fraser Basin Council, 2019). Building on this success, in 2014 the Pacific Salmon Foundation and the Fraser Basin Council launched a new initiative "Salmon Safe Communities in BC" in an effort to promote sustainable standards, and to encourage developers to mimic natural processes on unban sites through the introduction of low impact development.

To earn the Salmon Safe certification, and in order to be able to use the Salmon Safe logo for packaging and marketing farm products, the farm owners must have their farms and their related operations evaluated by a professional independent evaluator. It is important to note that the Salmon Safe certification does not relate to product quality itself, but rather it certifies and confirms that the landowners are following specific, strict, and sustainable environmental standards. The majority of these standards include sustainable operation practices, and stormwater management solutions that encourage the introduction of low impact development designed to mimic natural processes within urban environments. Since farms typically have large areas of permeable surfaces where rainwater can infiltrate into, Salmon Safe focuses its attention and recognizes farmers who seek to protect water quality, and stream habitats by promoting plant and wildlife diversity, protecting wetlands and natural woodlands, safeguarding natural areas, managing nutrient loads sustainably, using efficient irrigation practices, adopting natural methods to control weeds and farm pests, improving passage for migrating fish, controlling erosion by cover cropping bare soil, and maintaining a buffer of vegetation and trees along stream banks (Fraser Basin Council, 2019).

1.6.1. How Problematic Is Improperly Managed Stormwater for Salmon Health and Salmon Populations?

Salmon Safe BC states that polluted stormwater is the largest threat to the health of urban watersheds in the Pacific Northwest, and pollutants such as petroleum, heavy metals, pesticides, and construction sediment severely compromise downstream marine health (*Salmon Safe - Urban Site Certification Program*, 2017). The goal of this organization is to inspire and guide landowners to consider sustainable stormwater solutions that have positive impacts on downstream watersheds.

Salmon Safe BC concurs that the process of urbanization usually converts formally forested land, agricultural land, or permeable land into buildings, parking lots, roads, and other impervious surfaces in which rainwater cannot infiltrate into. During the interview process, it was noted that even the landscaped areas found on newly built development sites are often compacted with structural soil and are missing a significant amount of the original topsoil that would normally exist on a natural site. This can result in a hydrologic environment where surface runoff replaces the natural soil infiltration and evapotranspiration process which would typically occur under predevelopment conditions (*Salmon Safe - Urban Site Certification Program*, 2017). Once a site is developed and fully operational, planners and engineers at the District of North Vancouver often notice that vehicular traffic, on-going landscaping, and other routine site maintenance activities usually deposit large amounts of contaminants such as heavy metals, petroleum, pesticides, fertilizers, and bacteria in the area. During a rain or storm event, unlike in predevelopment conditions, rainwater is now unable to infiltrate into the ground, and harmful contaminants generally wash off the site's surface. The polluted water is then usually directed into the city's storm network before it is finally conveyed at high volumes into receiving bodies of water. If sites discharge into a stream or creek, the excess post-development surface runoff can increase the frequency and magnitude of peak flows, and this subsequently lengthens the duration of high flows. Participant 1 discussed that this significant alteration of natural flow regimes usually modifies and degrades stream habitats by eroding the channel beds and banks, scouring spawning gravels, and removing important stream structures. When a stream experiences higher flows over an extended period of time, this can directly impact salmon health due to the stress that is associated when fish are forced to live and function in streams with higher velocities. This stress can impede salmon migration and simultaneously sweep away food sources and organisms that healthy salmon populations rely upon in naturally undisturbed streams (Environmental Law Clinic, 2010, p. 18).

In addition to the disruption of flow regimes in streams and creeks, the pollutants found in stormwater runoff are usually very toxic to salmon and their invertebrate food sources. During the interview process, I was told that toxicity found in heavy metals such as copper and zinc are unquestionably detrimental to salmon health and other aquatic biodiversity. Other contaminants commonly found in salmon habitats include heavy metals, petroleum products, combustion by-products, and industrial, commercial and household chemicals which negatively affect the salmon population’s life-sustaining functions, and impact their feeding, growth, migration, and reproduction (*Salmon Safe - Urban Site Certification Program*, 2017). Unhealthy salmon are also generally slower, less coordinated, and more susceptible to predators when compared to their healthy counterparts.

1.6.2. **How Can Buildings Be Salmon Safe?**

Salmon Safe BC recognizes that if cities continue to densify, and urban developments fail to consider the implementation of sustainable stormwater management solutions, this could have long-term impacts on aquatic biodiversity, and salmon health even if the sites in question are not located directly adjacent to a stream or watercourse. The program states that stormwater runoff from impervious surfaces is the largest non-point source of pollution in urban areas (*Salmon Safe - Urban Site Certification Program*, 2017).

Salmon Safe BC argues that landowners can help protect salmon habitats by actively preventing or reducing runoff from their buildings and parking lots from entering the city’s storm network. In order to achieve this, the program actively promotes the use of low impact design solutions such as: raingardens, vegetation buffers, and permeable paving to capture and infiltrate rainwater at its source, thereby mimicking natural processes in urban environments. Salmon Safe BC also encourages property owners to collect stormwater and use this as grey-water to help reduce a building’s dependence on potable water and municipal water resources. The goal of Salmon Safe BC is to help encourage and inspire sustainable designs which have positive impacts on downstream watersheds for commercial campuses and residential communities.

The Salmon Safe certification has received a lot of attention in recent years. Many municipalities including the District of North Vancouver host Salmon Safe webinars and information sessions to help educate municipal staff on certification programs that aim to secure sustainable stormwater management solutions and low impact designs for urban sites.

1.6.3. MEC Headquarters – British Columbia's First Salmon Safe Urban Site

On October 23, 2015, the Pacific Salmon Foundation posted a media release recognizing the newly built Mountain Equipment Co-op (MEC) headquarters building as British Columbia's first Salmon Safe urban site (Pacific Salmon Foundation, 2015). This certification is awarded to urban sites that have implemented progressive land and water management solutions. This building was designed using environmentally friendly landscaping practices, and included low impact development strategies such as rain garden swales to filter stormwater, and on-site features to capture and reuse rainwater. Mountain Equipment Co-op's distinctive headquarters building is located in Vancouver British Columbia on Great Northern Way across from China Creek Park.

David Marshall, the Executive Director of the Fraser Basin Council stated, "I commend MEC on its vision and leadership in meeting Salmon-Safe urban certification standards. Here is a good example of how environmentally innovative practices, even in the middle of a city, can help protect Pacific salmon by enhancing the water that ultimately flows back to streams, rivers, and marine habitats"(Canadian Business for Social Responsibility, 2015). The Fraser Basin Council routinely encourages British Columbian communities, businesses, institutions, and non-profit organizations to step up and demonstrate leadership within their communities by securing Salmon Safe certifications for sites that are either newly developed or significantly renovated. Developments and renovations often include office buildings, retail centres, school campuses, and parks in suburban and urban areas.

MEC was recognized by Salmon Safe largely because of their creative low impact, sustainable stormwater management solutions that closely mimicked nature within their urban site. Natural stormwater management solutions incorporated on this site included limiting potable water usage by 55% by incorporating rainwater harvesting and reuse strategies to irrigate the expansive green roof, and to flush toilets within the building. The design also captured stormwater within the parking lot and filtered polluted water through a bio filtration rain garden system to help cleanse and remove pollutants, while also incorporating an on-site landscape design using native drought-tolerant plants which required no herbicides or chemical pesticides (Pacific Salmon Foundation, 2015).

This thesis aims to draw lessons from organizations similar to MEC who have received recognition for environmentally conscious designs. This thesis will focus on organizations that have achieved success in implementing sustainable designs that manage runoff more naturally through the use of green infrastructure and low impact development. More specifically, this thesis will focus on lesson-drawing from the City of Philadelphia who similarly to MEC has received recognition and praise for their innovative Green Streets Design Manual. Section 2.5 of this thesis outlines a conceptual framework that determines when lesson-drawing can be successful, and Chapter 6 of this thesis utilizes the framework to evaluate whether lessons can successfully be drawn from the City of Philadelphia.

1.7. Separating Sewage from Rainwater – The Combined Sewer Problem and Its Effects on Aquatic Health

If developments discharge improperly managed stormwater into a combined sanitary and storm sewer system, the result can be even more problematic for aquatic health. Combined sewers are an out-dated system of pipes that were designed to collect and transport both sanitary sewage and stormwater to a wastewater treatment facility within a shared pipe system. During dry weather conditions when flows are moderate, these combined sewers generally have the capacity to convey both sewage and wastewater to a sewage treatment plants, where the polluted water can be treated and discharged appropriately. During wet weather events however, heavy rainfall and high volumes of improperly managed runoff can exceed the capacity of combined sewer systems. This can result in the excess untreated wastewater and stormwater to overflow directly into downstream waterways (City of Vancouver, 2019).

This type of system is antiquated and generally no longer used by engineers today when designing new sewer systems. Modern sewers are usually designed specifically to exclude surface runoff, or groundwater infiltration from entering the sanitary network; however, even cities such as Vancouver still have historic combined sewers in service today (Schooley, 1999).

Combined sewers are problematic for two major reasons: first, because municipalities incur a cost per litre for wastewater treatment. The addition of stormwater within these pipes increases the total volume of water that needs to be treated, and this consequently increases the municipalities' treatment cost. Second, during wet weather events, the volume of flow required to be retained within these pipes commonly exceeds the capacity constraints of the combined sewer system. When this happens, polluted stormwater mixed with raw untreated sewage generally overflows directly into clean local bodies of water via combined sewer outfalls. The release of sewage from a combined sewer outfall is referred to as combined sewer overflow (Podolsky & MacDonald, 2008, p. 9). Some of the largest and oldest cities around the world still have combined sewers in service today and during intense rainfall periods combined sewer overflows are still a common occurrence (Madoux-Humery et al., 2013, p. 4371).

Urbanization can further contribute to the problem of combined sewer overflows. As cities continue to densify and as populations continue to grow, the volume of sanitary sewage production increases since more individuals now flush toilets, shower, do laundry, wash dishes, and engage in other activities that ultimately increase sanitary sewage volumes. This increase in sewage production puts additional capacity demands on aging infrastructure such as combined sewers which were never originally designed to accommodate this new level of flow. Additionally, as cities continue to develop and as permeable surface areas become impervious, the increased volume of stormwater runoff places additional demands on combined sewer systems that may already be at capacity.

Climate change can also contribute to more frequent combined sewer overflows in a city because the more frequent occurrence of storm events, can generate significantly more stormwater runoff for combined sewers to manage. During intense rainfall periods, combined sewer overflows routinely discharge a mixture of raw wastewater and polluted stormwater at high volumes into downstream receiving environments. This polluted discharge can severely degrade the quality of the receiving waters by modifying their ecological functioning and by increasing the concentrations of mineral, organic, and microbiological pollutants (Madoux-Humery et al., 2013, p. 4371).

Engineers should seek to reduce the frequency of combined sewer overflow events, and make every effort to prioritize the reduction of these overflows due to the contamination risks that they pose to the environment and to drinking water sources (Madoux-Humery et al., 2013, p. 4371). Without direct intervention and mitigation, the combined sewer overflow problem will continue to become more problematic (Podolsky & MacDonald, 2008, p. 9).

The challenges highlighted above further reinforce the importance of sustainable stormwater management. During the interview process, participant 5 and I discussed that for newly constructed developments, planners and engineers at the District of North Vancouver often encourage developers to disconnect certain areas of their sites (such as roof leaders) from piped networks where appropriate. This direction is consistent with the direction provided in Metro Vancouver's Homeowner's Guide to Stormwater Management, discussed in Section 1.3 of this thesis. Participant 5 and I also discussed that where possible, runoff should be managed as close to the source as possible, by infiltrating water back into the ground and mimicking the natural water balance. In chapter 4 of this thesis, we suggest that this can be achieved through the implementation of green infrastructure and low impact development. This thought process of managing stormwater by mimicking the natural water balance is also consistent with the District of North Vancouver's environmental ISMP objectives.

1.7.1. **Combined Sewers in Vancouver**

In Vancouver the first sewers were built in the 1890's, and the first significant sewer replacements began in the early 1960's (Schooley, 1999). Even at this early stage in time, city engineers in Vancouver recognized how problematic combined sewers could be, and the city's first sewer separation program began in the 1970's in downtown Vancouver where the earliest sewers were first installed. In the 1970's a significant portion of the original West End sewers were rebuilt to modern standards. As a result of Vancouver's sewer separation program, the Drake Street outfall in Yaletown, and the Granville Street outfall below the Granville Street Bridge now only discharges stormwater with no sanitary sewage into local receiving bodies of water.

By the year 2050, the City of Vancouver plans to have all combined sewers divided into separate storm and sanitary pipes; however, this is not an easy task because the city has approximately 1,920 kilometers of sewer pipe, and originally approximately 34% of the existing sewer system was built before the 1930's (City of Vancouver, 2019). The city needs to make considerations to replace not only the combined sewers, but also the aging and damaged sewers that are now past their design life and are no longer able to meet the capacity demands of the modern city. In order to tackle this issue, the City of Vancouver plans on replacing water and sewer infrastructure at the rate of 1% per year, and in doing so, city engineers believe that this rate of replacement will keep sewers in good condition and prevent risks to the environment and public health (Schooley, 1999).

Cost considerations need to be taken into account when considering sewer separations, and sewer replacements of this magnitude. The City of Vancouver has chosen to implement a continuous sewer replacement strategy in an effort to spread the cost of replacing this infrastructure over many years. The majority of funding for this work comes from sewer utility charges, and a gradual pipe replacement program allows the city to distribute these costs more evenly across the ratepayers over time.

1.8. The Great Lakes Basin and the Importance of Safeguarding Water Quality

When examining the importance of sustainable stormwater management and watershed protection, it is important to discuss the Great Lakes Basin, since this is the largest freshwater ecosystem in the world, and it holds approximately one fifth of the world's fresh surface water (Brinker et al., 2018, p. 5). The Great Lakes include Lake Huron, Lake Superior, Lake Michigan, Lake Ontario, and Lake Erie, all of which are interconnected by a series of rivers, channels, and smaller lakes. Within the Great Lake ecosystem, scientists have discovered 46 species of plants and animals that cannot be found anywhere else in the world, and almost 280 species of plants and animals that are considered globally rare (Podolsky & MacDonald, 2008, p. 7).

It is a common misconception to assume that the Great Lakes are an open system that eventually flows into the ocean. Rather, each year only 1% of the water leaves the basin flowing into the Atlantic Ocean via the St. Lawrence River, and only approximately 1% of the water is replenished each year, whereas the remaining 98% of water can be considered to be a 'one time gift' from nature resulting from the remains of melted glaciers after the last ice age (Podolsky & MacDonald, 2008, p. 7). This statistic reinforces the importance of managing stormwater sustainably and responsibly in this highly sensitive area.

1.8.1. Urbanization and Associated Pollution Problems in the Great Lakes Basin

Over the last century, as the world has continued to urbanize, the Great Lake region has also seen tremendous economic growth. Currently approximately 42 million people live within the Great Lake Basin, and approximately half of this population draws their drinking water directly from this source (Podolsky & MacDonald, 2008, p. 7). Urbanization and densification have brought with them unprecedented levels of manufacturing, industry, and mining, all of which place a heavy environmental burden on the delicate ecosystem within the Great Lakes. Sources of contamination generally lie in both Canada and the United States.

Pollution most commonly enters the Great Lake Basin through point source pollution, or non-point source pollution. Point source pollution can be traced back to a single and identifiable source, such as the effluent discharged from a wastewater treatment plant, or industrial wastewater from a specific site. Non-point source pollution by contrast is pollution that results from many different sources, and an excellent example of this is stormwater runoff.

This thesis will not focus further on point source pollution, or non-point source pollution as both topics warrant further analysis due to the complexity of these topics. Rather, this thesis would like to draw the reader’s attention to the fact that one of the largest sources of pollution within the Great Lakes is municipal sewage and stormwater resulting from combined sewer overflows which can be understood as non-point source pollution (Podolsky & MacDonald, 2008, p. 7).

1.8.2. Storm and Sanitary Sewer Cross Connections

In many cities there are instances where storm and sanitary systems are interconnected by cross connections, and this can also pose significant overflow problems (Yousef et al., 1980, p. 425). Cross connections whether intentional, or unintentional occur where storm sewer connections are connected to the sanitary network, or sanitary sewer connections are connected to the storm network. Sewer cross connections are relatively common in cities, and either type of cross connection poses a threat to the quality of receiving waters (McKinnon & Posedowski, 2014, p. 2).

In Canada, wastewater treatment plants are designed to operate in accordance with strict provincial and federal regulatory requirements. During significant rain events, or during the spring snowmelt, waste water treatment plants commonly experience bypasses (City of Toronto, 2017). In Canada, all wastewater is required to be disinfected, even during bypass events. With newer wastewater treatment facilities, rainwater and sanitary sewage can be fully treated even during extreme rain events for a certain period of time. If weather conditions do not improve, and heavy rainfall continues, the total volume of stormwater and sanitary sewage could potentially overwhelm the treatment facility, and the plant may not be able to treat all sewage and stormwater in time. If this happens, a certain amount of the wastewater may be diverted around the biological treatment process (i.e. the waste water treatment process) in order to protect the treatment plant, and this diversion is called a “bypass” (City of Toronto, 2017). With newly designed wastewater treatment plants, the bypassed wastewater is usually still put through a screening, grit removal, primary treatment, phosphorous removal, and full disinfection process to ensure that the final treated water always meets provincial and federal requirements (City of Toronto, 2017).

Bypasses are necessary for a number of reasons when dealing with combined sewer systems. First, they help by preventing rainwater and sewage in combined sewers from backing up and potentially causing basement flooding, surface flooding, or property damage. Second, they prevent and protect wastewater treatment plants from flooding, which can cause serious damage to the mechanical and electrical equipment housed within these treatment facilities, thereby allowing the plant to continue functioning appropriately. Finally, they help protect chemical biological plant processes from damage, since an overwhelming flow of wastewater can potentially wash out the microscopic organisms needed for appropriate waste water treatment (City of Toronto, 2017).

1.9. Watershed Management and How Strategies Have Evolved Over Time

Before evaluating how sustainable stormwater management solutions can be implemented at the District of North Vancouver, it is important to understand how stormwater management strategies have evolved over time. Managing stormwater sustainably is an inherently complicated process, and issues associated with climate change can further complicate matters. Watershed management is the practice of managing natural resources within the basis of a physio-graphically defined watershed boundary, and this practice first began in Ontario with the establishment of Conservation Authorities following the events of World War II (Haley & Auld, 2000, p. 1). Over the years, the definition of watershed management has evolved and expanded, first from focusing primarily on flood control and erosion related issues, to today's definition which includes broader terrestrial and aquatic environments, as well as social issues related to the use of the natural environment. This redefined definition views watershed management within the lens of an inclusive ecosystem-based management framework (Haley & Auld, 2000, p. 1).

Managing watersheds from an ecosystem basis, requires watershed managers to recognize that all components of the natural hydrologic system are interconnected. This means that changes to one component of the ecosystem, can have significant impacts on other downstream ecological components. Examples of this can be apparent when looking at pollution and erosion problems occurring within watersheds, or within outfall areas.

In the 1970's it became widely recognized that urbanization often saw the removal of permeable areas and their replacement by impermeable surfaces, thereby generating higher volumes of surface runoff during rainfall events (Haley & Auld, 2000, p. 2). Once the natural environment had been changed, civil engineers, and planners often noticed significantly more runoff due to factors such as less evaporation, less surface depression storage, and consequently less infiltration of water back into the ground. By the year 2050, the United Nations World Urbanization Prospects report estimates that approximately 68% of the world's population, which is roughly 6 billion people, will be living in urban centres and there will be increased demands on urban water systems (Johns, 2019, p. 1377). This highlights the importance of ensuring that sites are built responsibly today and designed appropriately to manage runoff more sustainably in the future. This also highlights the importance of potable water conservation as discussed in Section 1.4 of this thesis.

Early attempts to manage the increased volume of runoff within rivers and streams were centered around stormwater management strategies that primarily sought to reduce peak flows in an effort to match post development peak flows to pre-development levels. Although this practice is common and still used today, this strategy fails to address all impacts of urbanization. Higher flow volumes and higher peaks have the potential of creating significant erosion problems along watercourses resulting in impacts to existing infrastructure, and most importantly degradation within the function of the aquatic habitats (Haley & Auld, 2000, p. 2).

Traditional urban stormwater management solutions attempted the rapid removal of stormwater by primarily relying on centralized conveyance systems such as curbs, gutters, and piped networks (Dhakal & Chevalier, 2016, p. 1112). Relying only on these systems alone to manage stormwater in a city can be problematic, and this can result in many adverse impacts on the environment such as hydrological disruption, groundwater depletion, downstream flooding, receiving water degradation, channel erosion, and stream ecosystem damage (Dhakal & Chevalier, 2016, p. 1112). This thesis encourages planners and engineers to use a combination of centralized conveyance systems, green infrastructure, and low impact development to manage urban runoff more sustainably. In order to mitigate some of the adverse impacts noted above, urban stormwater managers today are increasingly relying more on green infrastructure and low impact development solutions that promote on-site infiltration, restore hydrological functions of the landscape, and reduce surface runoff (Dhakal & Chevalier, 2016, p. 1112).

In addition to erosion issues, the water quality in many receiving bodies of water has been degraded to the point that many streams now support significantly different aquatic life, fewer fish, and changes to the aquatic environment have now begun to affect both the flora and fauna that exist within valley systems (Haley & Auld, 2000, p. 2). The term fauna refers to all of the animal life present within a particular region, and the term flora is the corresponding term referring to plants.

As we attempt to remedy many of the negative consequences and employ new initiatives and strategies in an effort to reduce the impacts that development has caused on natural systems, changes continue to occur within our watersheds as a result of our past and current actions. Once a watershed undergoes changes resulting from urbanization, the impacts to the watercourse may require between 35 and 200 years to adjust to its revised flow regime depending on flow channel soil conditions (Haley & Auld, 2000, p. 2).

Current strategies for watershed management now focus on working together with the dynamic aspects of the natural environment and its related natural features. Within the District of North Vancouver, an example of this could be managing watercourses based on their valley and stream corridors, and allowing for the natural processes of meandering streams as a component of a larger conveyance feature. These types of strategies related to natural heritage features within a watershed also allow watershed managers to integrate flexibility within the system. As a result, the concept of watershed management has evolved, and it is now focused on the ability to manage and plan within the system by treating stormwater as a resource, while making allowances for natural processes and changes to continue to take place.

The traditional management of watersheds from an aquatic perspective has typically focused on mitigating impacts to land use change for the portions of the hydrologic cycle where precipitation moves over land to receiving watercourses. Climate change can bring changes to the atmospheric components of this cycle, and changes in evaporation rates and the severity of storms, supplemented with increased temperatures could result in significant alterations within the natural ecosystem of a watershed.

To respond to many of these concerns, a growing number of municipalities in North America have now invested large portions of their budgets into water and stormwater management; however, many Canadian cities are still finding it difficult to adapt to climate events such as flooding (Johns, 2019, p. 1377). At the District of North Vancouver for example, aging infrastructure and undersized storm mains need to be replaced and upsized in order to adapt to changing weather patterns. Policy makers, planners and engineers have recently begun to look toward green infrastructure and low impact development to help mitigate some of these challenges (Johns, 2019, p. 1377).

1.10. How Climate Change Has Affected Cities, Natural Ecosystems, and Stormwater Management

Climate change is a consequence of increased production of greenhouse gases such as carbon dioxide within the atmosphere (NASA, 2020). The continued loss of natural resources, and the unsustainable burning of fossil fuels have led to changes in our environment, and consequences for future generations that researchers have only recently begun to understand.

Although this issue has gained a lot of publicity in recent years, and is now internationally recognized, our ability to reverse or stop the impacts of climate change can be somewhat limited due to the residence time of harmful gases within the earth's atmosphere, and this is important to understand when trying to manage stormwater (Haley & Auld, 2000, p. 4).

Current strategies to address climate change are primarily focused on reducing the production of greenhouse gases; however, due to global technological and economic capabilities, this approach may not be entirely possible in the near future. Over the next 50-70 years scientists and researchers are expecting greenhouse gases in our atmosphere to continue to increase to levels that are approximately double those of pre-industrial times, and as a result, climate change related events are expected to continue, if not worsen, in the near future (Haley & Auld, 2000, p. 4). Climate change is now widely expected to elicit a myriad of ecological, economic, and social effects, many of which are associated with changes in the quantity and timing of precipitation, and within an urban context, concerns associated with stormwater management are among the most frequently cited (Moore et al., 2016, p. 491).

In Canada for example, the average annual temperature is projected to increase between 1.8 to 6.3 degrees Celsius by the end of the century (Government of Canada, 2018). This trend in global warming is expected to be seen worldwide, and watershed managers must take this into consideration since climate change can significantly alter the volume of water that can be expected within a watershed.

Global warming is expected to contribute to possible decreases in soil moisture, and surface water runoff. Additionally, changes in atmospheric circulation patterns and storm tracks may also affect wind patterns, the frequency of storm surges, land erosion, and the intensity of rainfall in storm events.

Shipping activity, hydroelectric production, and the stability of aquatic nearshore ecosystems in the Great Lakes could be affected by lower lake levels and warmer temperatures. Additionally, if a warmer climate contributes to a decline in water supply, and population growth continues to expand, the demand for clean potable water will inevitably increase. This could lead to a greater competition for water, and this example highlights the importance of water conservation and water reclamation strategies in cities.

Longer, warmer weather events could be beneficial from an agricultural perspective if soil moisture levels are addressed appropriately. Extreme and unanticipated changes in weather events can result in detrimental impacts for ground water supplies, lake levels, and urban environments. If natural systems are sufficiently changed or compromised by climate change, this could threaten the species and organisms living in sensitive natural ecosystems.

At the other end of the spectrum, if cities receive unexpected intense rainfall events at altered frequencies of occurrence, urban infrastructure, and property could be at risk of damage from flooding and storm sewer surcharging. In cities with combined sanitary and storm networks the risk of overflow can be greater. In order to protect people, property, and infrastructure from damage, adaptation measures are necessary in cities (Brudler et al., 2016, p. 394).

In many cities, climate change has contributed to the increase of the intensity, duration, and frequency of storm events, and watershed managers are now seeing intense storms occurring with shorter lead periods. More problematically, as a result of climate change, current weather forecast technology is generally less accurate in predicting the timing of rainfall events or anticipating the amount of rainfall expected within a certain area. This can be problematic for watershed managers as evidenced by the intense and unexpected storms received in recent years. Global warming can also increase the number of mid-winter melts caused by warmer winter temperatures, and this additional runoff can pose varying threats and impacts on infrastructure, watersheds, and watercourses. Changes in snow melt, and related snowmelt runoff may also impact other water management issues such as reservoir operations. To respond to some of these concerns, new ways of managing runoff are increasingly utilized today, and recently, many of these strategies focus on local infiltration, and the retention and gradual discharge of surface water through the implementation of green infrastructure solutions around the city (Brudler et al., 2016, p. 394). For example, countries such as Denmark, Norway, Germany and the Netherlands, are currently using green infrastructure solutions and landscape based stormwater management systems in an effort to adapt their cities to precipitation changes brought about by climate change (Backhaus & Fryd, 2013, p. 52).

Although human beings and engineered systems may be able to adapt quickly to climate change, natural ecosystems and wildlife are not able to adapt as quickly to sudden, large scale changes to their environments and ecosystems. As an example of this, certain shoreline wetlands could migrate lakeward, while other more enclosed wetlands could be at risk of drying up. If wetlands dry up, this could result in significant implications for organisms, fish, and wildlife living within the altered ecosystem (Haley & Auld, 2000, p. 5). This example highlights an additional layer of stress to natural species and ecosystems whose habitats may already be threatened by the ongoing impacts of urbanization and other human activities. Multiple stresses to natural environments can exacerbate local species extinction and increase the likelihood of invasion by exotic invasive species.

Stormwater management under climate uncertainty is a concern in both urbanized communities, and areas that are currently undergoing land use changes (Moore et al., 2016, p. 491). For example across Europe, aging sewer systems and current changes in precipitation patterns brought on by climate change have led to urban flooding, combined sewer overflows, and water quality problems in receiving bodies of water (Backhaus & Fryd, 2013, p. 52).

Consistent with our statement earlier, in the Lower Mainland, watershed managers are noticing significant increases in the intensity, frequency, and duration of rainfall events. Within urban environments, concerns associated with stormwater management are among the most frequently cited (Moore et al., 2016, p. 492), and the reason for this is because climate change has rendered one of the key facets of urban drainage design (a satisfactory precipitation frequency distribution) to become questionable at best (Rosenberg et al., 2010, p. 324). This is problematic because the infrastructure in a city is designed specifically to manage predicted precipitation distributions, and when this changes, there is an increased risk of flooding, property damage, pollution, and public health concerns.

In urban stormwater networks, issues such as flooding arise when the capacity of components within a system are overwhelmed and storm runoff accumulates on the surface. A drainage system's ability to respond to sudden climate events such as longer unexpected storms are usually site dependent. Newly developed sites are generally better suited to manage the unexpected storm events, since their on-site stormwater management systems are designed and built to withstand the events that are expected to result from climate change (Denault et al., 2002). Older development sites would generally expect to see increases in flooding and sewer overflows since the infrastructure in place cannot accommodate the storm events resulting from climate change (Horton et al., 2010, p. 183).

Research is currently being conducted on how to enhance the resilience and the ability of existing systems to function appropriately despite the complications of climate change. Some examples of this could be as simple as re-directing the route of impervious runoff to lawns, or engineered stormwater infiltration areas in order to help mitigate climate change induced flooding (Waters et al., 2003, p. 762). This strategy is frequently used in cities, and the potential for natural vegetative cover to partially mitigate projected increases in surface runoff and flooding is becoming a more widely used strategy among civil engineers, planners, and urban designers. The success of this strategy encourages designers to consider the use of green infrastructure and low impact development as an integral component of adaptation planning (Gaffin et al., 2012, p. 704).

As stated earlier, climate change has become a rising concern for watershed managers. The intensity of rainfall during storm events has increased significantly, and this is especially true for short duration storm events. Extreme rainfall events are generally predicted to occur more frequently, and this expected change in precipitation patterns can render existing stormwater management practices and infrastructure to be more prone to failure. As weather patterns change, it is important for designers to look toward holistic, robust stormwater management systems that seek to manage rainwater at the source, along the conveyance network, and finally at the end of the pipe. Green infrastructure, and low impact development strategies are adopted in an effort to reintroduce natural processes within urban environments and adapt to changes in precipitation patterns.

1.10.1. The District of North Vancouver's Climate Change Adaptation Strategy

The District of North Vancouver's Climate Change Adaptation Strategy seeks to prepare the municipality for the upcoming expected changes in weather events. This strategy includes increasing climate action resilience and attempting to reduce avoidable long term costs or impacts associated with climate change.

During the interview process, participant 5 and I discussed the unexpected storm events that have occurred in the District over the last 4 years, and the fact that in 2016, the District updated their IDF curves to account for the increased intensity, duration, and frequency of rain events. More specifically, the average annual precipitation in the District is projected to increase by approximately 5% overall, but expected to decrease by 18% in the summer months (The District of North Vancouver, 2017b, p. 2). During dry summer months when precipitation is limited, it becomes increasingly important to manage water resources appropriately and conserve potable water when possible as discussed in Section 1.4 of this thesis. It is also important to note that more precipitation is expected to fall during extreme storm events, with 33% more precipitation falling on the wettest 5% of days, and 58% more precipitation falling on the wettest 1% of days (The District of North Vancouver, 2017b, p. 2).

Of the 12 action objectives stated in the District's Climate Change Adaptation Strategy, objective 3.1 is noteworthy from a stormwater management perspective, as it promises to complete the District's Integrated Stormwater Management Plan and implement the recommendations to reduce the impacts of runoff and maintain the health of watersheds. The District also makes note of collaborating with its neighbour The City of North Vancouver on stormwater management, which is appropriate since the City and the District share watersheds that cross jurisdictional boundaries. Stormwater in the District is primarily managed by directing road runoff into storm sewers; however, with climate change on the rise, participant 5 and I discussed the fact that that District staff are noticing longer, more intense storms, with more runoff to manage. We discussed that managing stormwater in this way can problematic if all runoff is directed into storm sewers, since only relying on piped conveyance systems can create flooding, erosion and water quality issues in creeks, streams, and riverbanks.

Chapter 2. Literature Review

To understand how sustainable stormwater solutions can be incorporated into public policy, one must first understand how policy change occurs in government and public bureaucracies. Within this section of the thesis, I will incorporate and review literature regarding policy change with a specific focus on lesson-drawing and the voluntary transfer of information. I will also develop a conceptual framework using lesson-drawing and policy transfer to assess how likely it is that the green infrastructure and low impact development solutions discussed in Chapter 4 will be utilized when analyzing my results.

2.1. Policy Change – What is Lesson-Drawing and Voluntary Transfer of Information?

Changes in policy will likely be required in order to successfully implement the green infrastructure and low impact development solutions outlined in the data and analysis section of this thesis. Policy transfer is a method of implementing changes in policy. Evans defines policy transfer as a theory of policy development that seeks to make sense of a process, or set of processes in which knowledge about institutions, policies or delivery systems at one sector or level of governance is used in the development of another sector or level of governance (Evans, 2006, p. 480). The basic concept of policy transfer is to utilize successful aspects of policy within other jurisdictions to improve upon existing policies that are stagnated or outdated within a recipient jurisdiction.

Evans outlines three different processes of policy transfer. The first is a voluntary transfer of policy or lesson-drawing. This process involves a rational proactive approach to dealing with problems or issues within public policy. Voluntary transfers can emerge from various sources such as: the identification of public or professional dissatisfaction with existing policy due to poor performance, new agendas resulting from change in government, political strategies aimed at legitimizing conclusions that have already been reached, and attempts by policymakers to upgrade items of policy agenda to promote political allies and neutralize enemies (the last scenario noted is likely to occur close to an election cycle).

The second type of policy transfer is a negotiated transfer whereby recipient governments or jurisdictions are encouraged by donor countries, global financial institutions, or supranational organizations to introduce policy change in order to secure grants, loans, and other funding. This is an exchange of ideas, but it has a fairly coercive nature as the recipient must comply in order to receive monetary contributions that they heavily rely upon. Evans provides an example of developing countries' policy being dictated by the World Bank or the International Monetary Fund in exchange for funding (Evans, 2006, p. 481).

The third and last type of policy transfer outlined by Evans is direct coercive transfer in which one government or jurisdiction is forced by another to introduce constitutional, social, and political changes against its will and the will of its people. Evans uses imperialistic practices of many former and current European colonial powers over its dominions as an example of direct coercive transfer of policy.

This thesis will focus on voluntary transfers of policy, more specifically lesson-drawing, in order to improve upon existing policies surrounding stormwater management in an effort to secure more green infrastructure and low impact development solutions in the District of North Vancouver.

Richard Rose in his article '*What is Lesson-Drawing'* defines lesson-drawing as determining under what circumstances and to what extent can a programme that is effective in one place transfer to another (Rose, 1991, p. 3). Dolowitz and Marsh, in their article reviewing literature on policy transfer critique the manner in which Rose uses policy transfer and lesson-drawing interchangeably (Dolowitz & Marsh, 1996, p. 344). As noted above, policy transfer can have different natures, whereas lesson-drawing is a rational, deliberate process that is voluntary.

Rose's work challenges the assumption that each country or jurisdiction has problems that are unique to them. He acquiesces that there is truth to this assumption up to a certain point, as different countries have different political and governmental structures which can raise different challenges in terms of problem solving (Rose, 1991, p. 3). He notes however, that problems faced by most countries are not unique, and are shared by most countries. Public concerns that must be addressed by government such as education, social security, and health care are common across many countries and continents. Rose goes on to say that when faced with a common problem, policymakers can draw lessons from how their counterparts reacted, whether it was successful or problematic, in order to improve upon the issue domestically (Rose, 1991, p. 4).

Evans in his review of Rose's book, "Learning from Comparative Public Policy: A Practical Guide" further explains what Rose deems is lesson-drawing, and what more importantly is not lesson-drawing. Based on Evans' review, Rose states that lesson-drawing is deliberate, and omits information that is interesting but non-essential, while only including essential aspects that make a programme work (Evans, 2006, p. 483).

Lesson-drawing shares the assumption that all countries will adopt the same approach in response to a common stimulus. Rose goes on to specify that lesson-drawing is an intentional exercise that involves research and does not include personal past experiences. This is an important point to note, or there may be no boundaries as to what counts as 'lesson-drawing' (Evans, 2006, p. 484).

Rose notes that lesson-drawing can only be successful if the programme that is transferred is compatible with the value system of the recipient and builds on existing strengths. Rose's book on Comparative Public Policy outlines ten steps recommended to practitioners in order to evaluate whether a foreign programme should be applied locally or not.

2.2. Lesson-Drawing – Who Are the Learners, What Is Learned and To What Effect?

Before we evaluate an effective way to introduce new policy, or change an existing policy, it is important to understand why policy change occurs in the first place. Bennett and Howlett note that this is not a well understood phenomena, and evaluate how the orthodox viewpoint on this matter has changed over time (Bennett & Howlett, 1992, p. 275).

Where previously the consensus was that policy change occurred due to conflict and social pressures, currently the widely held view is that learning is the root of policy change rather than conflict. Civil servants, consultants, policy specialists and their ability to shape intellectual premises and performance measures employed by policy makers are all important sources of influence that drive policy change (Bennett & Howlett, 1992, p. 275).

According to Bennett and Howlett, it is now a widely held view that states or public organizations are more than just a means to address conflict within society; however, they note that there is still a lack of clarity with regards to the nature or agent of policy change. The lack of clarity on the source of change is due to different ideas surrounding what learning means. Bennett and Howlett discuss the different views held by Peter Hall and Hugh Heclo to highlight two major viewpoints on what learning means in terms of policy theory (Bennett & Howlett, 1992, p. 276).

Hall states that learning occurs due to organizations' desire for better goal attainment, and this is a more proactive method of adjusting policy due to less than ideal results from previous policies in place. Heclo on the other hand notes that learning is more a reactive action that occurs due to do some form of social conflict or issue that requires change. These are two different views on why learning and policy change occur, as one puts more of the onus on the government to want to learn and change, while the other notes that it is due to unsuccessful results from the traditional policies or the status quo.

Bennett and Howlett point out that these differences in concept are important because while many may use the same term, they have different ideas on what learning means and why it occurs in the first place. Understanding why an author believes learning is occurring is important because if an author believes learning occurs due to social conflict, we can ask the question: is the transfer of information truly voluntary?

Bennett and Howlett's article goes on to evaluate the components of competing concepts. These components are: who learns, what is learned, and what is the point of learning, or what is the goal being sought after by the learners (Bennett & Howlett, 1992, p. 278). For the purpose of this thesis, and in order to develop my conceptual framework, I will be focusing on the critical components of lesson-drawing as was developed by Richard Rose, in order to analyze whether this concept can be used to effect policy change with regards to stormwater management.

Richard Rose's view on why governments search for knowledge appears to align with Heclo's, in that he argues that it is not a usual activity to pursue knowledge, but it is reactionary due to dissatisfaction with the status quo (Bennett & Howlett, 1992, p. 282). The difference from Heclo's view however, is that Rose does not narrow the agent of learning to social conflict. While he argues it is reactionary, it is not necessarily due to conflict that is brought on by society, but can be due to internal members within the organization noting a need for change. Rose goes on to elaborate that lesson-drawing occurs when policymakers rely on expert professional communities for advice on policy change. These communities are defined as knowledge-based networks of individuals with a claim to policy-relevant knowledge based on common professional beliefs and standards of judgement.

Rose goes on to say in his article, "What is lesson-drawing" that policymakers are driven by the need to address dissatisfaction with programmes and policies that have negative consequences or results (Rose, 1991, p. 10). He notes that policymakers do not engage in research like students of higher learning institutions are expected to, because policy makers are not driven by idle curiosity, but the need to solve a problem with the existing policies. Rose further states that the option of doing nothing, or not changing policies is always the most preferred route of policymakers since it requires the least investment of time and resources. More specifically, if there is no problem or issue, according to Rose, policymakers see no need to fix what is not broken (Rose, 1991, p. 10).

Rose elaborates that lesson-drawing is initiated when routine is disrupted, and policymakers can no longer operate under the current conditions, or within the status quo of the existing policies or programmes. In terms of stormwater management, the disruption noted is the damage to the environment as a result of the pollutants that end up in streams, creeks, and other receiving bodies of water. This damage is evaluated through studies of salmon habitats that show a relationship between pollutants in the habitat and its deterioration. The environmental ramifications of pollutants in bodies of water is what constitutes the gap between aspirations and achievements that Rose says is necessary to begin the search for lessons.

If we draw a connection to what the agent of learning for stormwater management is, and who learns and draws lessons, the expert professional communities that policymakers can call upon would be engineers, environmental scientists, and city planners to determine whether current policies in place are still effective or require changing and updating to meet the growing needs of the planet and the ecosystem. In this scenario it is not just the players within government or state actors who learn, but essentially the entire network involved in developing policy for sustainable stormwater solutions that ‘learns’. This would include state actors, external experts, and the entire network of the knowledge-based community.

When it comes to what is being learned and the learning process itself, Rose points out three options to reduce discord with existing policies. The first option is looking back at history and how problems with policy were solved at that point in time. The second is looking into the future to speculate, forecast and theorize, and the third is to draw lessons from existing successes within policymaking in other jurisdictions (Bennett & Howlett, 1992, p. 284). Lesson-drawing specifically involves a comparison of policy that has seen successes elsewhere with the dissatisfaction of the existing policy that is no longer conducive to the changing environment and societal norms. With regards to stormwater management specifically, I will draw lessons from the implemented and currently used City of Philadelphia’s Green Streets Design Guideline to determine whether it is appropriate to apply at the District of North Vancouver.

With regards to the effect of policy changes, Rose argues there are five common elements of lesson-drawing and Rose generally appears to focus on instrument and programme changes. The results from lesson-drawing can be one of the following: 1) a program is copied from one place to another, 2) a program in one jurisdiction is used as a model or outline but the details are modified to meet the needs of the recipient jurisdiction, 3) a hybrid approach is taken where facets of each program are combined, 4) an approach built on hybridization where multiple programs are combined into a cohesive synergized program, and 5) inspiration is drawn from a jurisdiction and is used to facilitate improvements to domestic or recipient jurisdictions (Bennett & Howlett, 1992, p. 287). I will use the second approach, where I will use the City of Philadelphia’s Green Streets Design Guideline as a model from which I will detail specific sustainable stormwater management solutions that should be considered within The District of North Vancouver.

In their conclusion Bennett and Howlett discuss the lack of empirical work surrounding the notion of learning being used as a corrective to the traditional conflict resolution model. They further note that concepts could be framed in a manner where connotations and denotations are clear and their meaning must be more succinct (Bennett & Howlett, 1992, p. 288). They attempt to provide a synthesis of the various views on learning rather than reject any one concept. For the purposes of this thesis, I will not delve into how Bennett and Howlett managed to combine the different concepts of learning into a mosaic of sorts, as I am focused on using lesson-drawing from different jurisdictions to address issues within existing policy surrounding stormwater management.

2.3. Policy Transfer- The Actors Involved in Policy Transfer and Factors That Can Constrain Policy Transfer

Dolowitz and Marsh identify six categories of actors involved in policy transfer and qualify that in any case more than one category of actor is likely to participate in said transfer. The six categories noted are: 1) elected officials, 2) political parties, 3) bureaucrats or civil servants, 4) pressure groups or lobbyists, 5) policy experts, and 6) supra-national institutions (Dolowitz & Marsh, 1996, p. 345). The article notes that the roles played by the first four categories in policy transfer is obvious and does not elaborate on the roles they play.

Dolowitz and Marsh highlight the roles played by policy experts by noting that they play an important role in the transfer of policy. The reason for this is because their specialized study on the subject matter results in them having a wide array of contacts with vast sources of knowledge that can be shared. In addition, they discuss supranational organizations' roles in policy transfer, as historically these organizations have always encouraged an exchange of ideas between countries.

The role played by supranational organizations is indirect in comparison to those played by policy experts and actors within government. This is because they act as a catalyst for transfer, as opposed to policy experts and members of government, since they have little say in what or how much gets transferred. The authors note that the literature they are reviewing minimizes the role played by supranational organizations in coercive transfers (Dolowitz & Marsh, 1996, p. 346). While supranational organizations may appear to not be decision makers like elected officials, political parties, or bureaucrats, the pressures they can exert do hold significant influence over these actors within government and their roles should not be discounted.

For the purpose of this thesis, I will be focusing on policies transferred by bureaucrats or civil servants as I will draw lessons from the City of Philadelphia in order to recommend the implementation of green infrastructure and low impact development strategies for sustainable stormwater management. It is important to note however, that while this thesis draws lessons from a municipality, there is likely a significant amount of policy being transferred from policy experts and entrepreneurs that helped shape the Green Streets Design Manual being used by the City of Philadelphia.

Dolowitz and Marsh note that the ability to transfer a policy or a programme depends on the complexity of its nature. The more complex, the harder to transfer. The authors refer to Rose’s hypotheses regarding constraints in policy transfer. Per Rose there are six potential explanations that could determine whether policy transfers could or could not occur. 1) Does the programme have a single goal or multiple? Programmes with single goals are more likely to be transferable. 2) Is the issue simple or complex? – if the discord with the existing policy or program is not easily remedied, it will be harder to draw lessons and transfer policy. 3) How direct is the relationship between the problem and the solution? – the more direct, the easier the transfer. If the problem and solution are co-related but have no causal relationship, this will be harder to transfer. 4) What are the side effects of the policy? – The fewer the perceived additional issues that could arise from policy transfer, the easier it will be to implement. 5) How much information is available on the donor programme? – The more information recipient jurisdictions have, the easier it will be to draw lessons. Lastly, 6) How easily can outcomes be predicted? – If it is simple enough to create a forecast or a model of what the results of the transfer will be, the easier it will be for the transfer to occur (Dolowitz & Marsh, 1996, p. 353).

Dolowitz and Marsh note that the system inherited by current recipients looking to change policy or engage in policy transfer often dictates how easy the transfer will be. This is not included as one of the six constraints, but the authors note it must be considered when determining if policy transfer can occur.

The authors also evaluated constraints such as institutional and structural constraints, drawing a comparison between the United States’ structure of checks and balances and the United Kingdom’s unitary system (Dolowitz & Marsh, 1996, p. 354). The British system allowed for policy transfers from the United States, whereas the structure of the United States' political system would be less likely to facilitate easy international policy transfers as the executive branch (the president) is typically more involved with international relations but most major policy changes need to go through the legislative branch (Congress) to be implemented.

Rose notes that the efficiency of a bureaucracy, as well its size and funding will determine how easily policy may be transferred. Even the most desirable and the least politically contentious transfers will not be implemented if the recipient organization does not have the technical or economic resources to see it through.

In this thesis, I will use the above-mentioned constraints to evaluate whether the District of North Vancouver will be able to draw lessons from the City of Philadelphia's Green Street Design Manual in order to recommend the implementation of green infrastructure and low impact development solutions for sustainable stormwater management.

2.4. Policy Transfer- Has it Been Done Before? A Look into The Successes and Constraints of The Transfer of The Business Improvement District (BID)

In her article, "Importing Ideas: The Transnational Transfer of Urban Revitalization Policy", Lorlene Hoyt explores how policy transfer was operationalized. Hoyt does so by demonstrating through personal interviews and organizational surveys the successful transfer of the Business Improvement District Model (BID) to eight different countries. She notes that the transfer was successful despite the participants having divergent histories and different political and socio-economic climates.

Hoyt defines Business Improvement Districts (BIDs) as a new form of government created by property and business owners through state authority. BIDs have the power to impose taxes, provide collective services, and supplement public funding to attract visitors and investors, and improve the overall pedestrian experience (Hoyt, 2006, p. 221). The three main goals of the BID are to be delightful, safe, and clean. Hoyt goes on to elaborate that BIDs promote safety by implementing crime prevention programs and provides examples of various BIDs within Canada that supplement policing efforts with private security. In order to promote 'delightfulness', BIDs engage in aggressive marketing campaigns that often feature a single appeal that plays to a niche market. To achieve its goal of cleanliness, BIDs carry out various activities such as mechanical and manual sweeping, high pressure washing, and graffiti removal for example. Hoyt uses the City of Philadelphia's Center City BID as an example of a BID that administers its own sanitation program while other BIDs contract this service out.

Hoyt's point in providing this information is that, while BIDs may take different approaches in how they achieve these goals, they share the same goals. This suggests that the BID model has been transferred not by copying programmes in specific jurisdictions, but by using the model for goal attainment while modifying and tailoring the programme to meet the unique needs of recipient jurisdictions. This ties into the second method of lesson-drawing in Richard Rose's common elements of lesson-drawing, as previously discussed in Section 2.2 of this Literature Review. In this thesis, I will demonstrate how this result of lesson-drawing can be achieved by using components of the City of Philadelphia's Green Streets Design Manual as a model while still maintaining the same goal of achieving sustainable stormwater solutions.

Hoyt discusses the origin of BIDs and how they came about by noting the decline in retail sales and commercial growth in the City of Toronto in the 1960's due to the rise of suburbanization. She attributes part of the decline to the completion of regional shopping malls such as Yorkdale, and the completion of the Bloor-Danforth subway line, as these made it easier for people to commute into the city for work and shop closer to home. This led a jewelry store owner named Neil McLellan to begin a dialogue between business owners and various organizations including several government organizations and bureaucrats that would eventually lead to legislation passing to create the world's first BID – Bloor West Village (Hoyt, 2006, p. 229).

The first BID program had a modest budget but focused on streetscape improvements and special events. The first year saw the installation of large planters, new benches, trash receptacles, banners, and lighting for example. They worked with regional organizations to remove utility poles and move services underground. Hoyt notes through an interview with a long-term business owner that these improvements increased the number of visitors to the area (Hoyt, 2006, p. 230).

With regards to how the BID transfer occurred, Hoyt notes that it was transferred across various cities and provinces in Canada from the 1960s to the 1980s in large part due to encouragement from local and provincial governments that facilitated legislation to be passed. This is evidenced by the Province of Ontario making infrastructure grants available to BIDs in the 1970's. Hoyt is unable to locate or determine how the BID policy was transferred to the United States but uses the City of Philadelphia's adoption of the programme as the case study for successful lesson-drawing and policy transfer.

Like the City of Toronto, Philadelphia experienced a decline in retail sales and commercial growth due to suburbanization. This led local business associations made up of business owners to begin a dialogue with the City of Denver, a city that had successfully imported the BID model. This began a four-year long endeavor of research, communication with state actors, understanding of various statutes, and feasibility studies in hopes of implementing the same model in Philadelphia. The result was the legislation passing and the bill being signed into law in 1990, and the BID becoming operational in 1991. Hoyt notes that not only was the transfer of the BID model successful in the City of Philadelphia, but their Center City BID became a model for export. Hoyt attributes this success to the program itself for being visible, possessing considerable wherewithal, and to the network of 'dedicated, creative, and charismatic professionals who worked toward lesson-drawing from other jurisdictions (Hoyt, 2006, p. 231).

The article further describes how the BID model migrated to various countries such as New Zealand and South Africa, and she discusses the existence of the BID model in various European nations such as the United Kingdom, Serbia, and Albania to name a few. Hoyt notes that these BIDs are not identical to the original BID in Toronto, or even the 'ideal' of the Center City BID in Philadelphia, but are tailored to the unique structures, political and socio-economic climates of the recipient locales (Hoyt, 2006, p. 233).

Hoyt also discusses jurisdictions that have not adopted BIDs but are in the emergence stage of policy transfer. Hoyt defines the emergence stage of policy transfer as the stage that involves research and study of BID policies and activities such as drafting and lobbying to implement BID legislation in their homeland (Hoyt, 2006, p. 228). The article notes that while BID organizations do not exist in countries such as

Japan, Austria, and Germany for example, the consideration of legislation is an important part of policy transfer as this is the stage that occurs right before adoption. She uses Japan as an example and notes that while BIDs are not formally adopted, Japan has passed legislation to create Town Management Organizations to assist with revitalization of urban areas (Hoyt, 2006, p. 234).

Hoyt also discusses municipalities where there has been resistance to the adoption of BIDs and where transfer of policy has not occurred. It is important to analyze why these failures occur to identify constraints and to determine whether a transfer will be successful or whether lessons can be drawn in any given circumstance. Hoyt outlines three reasons why BIDs do not get established when there is legislation in place that supports it. First, there is a lack of leadership necessary to form the collective vision, second, they lack financial means or, third, they face opposition from a large portion of property and business owners in the area likely due to the tax involved in funding the BID. Hoyt also credits a change in government as a deterrent against implementing new policy (Hoyt, 2006, p. 234).

Hoyt uses the City of Boston as the main example for resistance of the BID, as this locale had an abundance of it. She attributes the resistance to state laws, union opposition, and a contentious legislative environment (Hoyt, 2006, p. 235). The main point of contention was a state law that allows property owners to opt out of participating in the BID. This was added due to the position of elected officials who were opposed to new taxes, and that the BID revenues would interfere with the limit for property tax levies in the state. Hoyt notes that other organizations in the state found work arounds for the opt out clause by passing a home rule petition that included mandatory participation in the BID. This requires approval from Boston City council as well as from the legislature. While the City council approved the workaround, the BID has not been adopted by the City of Boston for their Downtown Crossing BID. Vocal opposition from the Massachusetts AFL-CIO, the Boston Police Patrolmen's Association, and some local elected officials is attributed to the failure of adoption. The reasons for the opposition were numerous, and included excessive pay, and concerns regarding privatizing jobs by replacing police officers with security guards to achieve the safety goal of the BID (Hoyt, 2006, p. 235).

2.5. Policy Transfer Framework- When Can It Be Done Successfully and What to Consider for Potential Policy Failures

In this section, I will present a conceptual framework with which I intend to evaluate whether the District of North Vancouver can draw lessons or initiate a policy transfer from international (The City of Philadelphia), regional (Metro Vancouver), and local (City of Victoria) governments. The framework will provide a basis to answer the question, "can this programme or policy implemented in a different jurisdiction be successful in the DNV?". I will include points from the literature reviewed above, while also including themes and ideas noted in other articles from authors on policy transfer as well as policy failure.

Richard Rose notes that policy adoption alone is not the only result of successful lessons that can be drawn. Lessons can be positive or negative, and a lot can be learned from decisions made not to transfer a policy from a different jurisdiction. In other words, learning what not do, and the decision to not a adopt a policy from another locale is also a form of lesson-drawing. Rose makes a distinction about positive and negative lessons that can be drawn.

For the purposes of this thesis, I will draw positive lessons from other locations such as the City of Philadelphia, and the City of Victoria with the goal of policy transfer and adoption in mind. While one can spend an abundance of time evaluating the decision making of other municipalities that led to policy failures with regards to sustainable stormwater solutions, it is beyond the scope of this paper. Notwithstanding the value that can be added from learning 'what not do', the goal of this thesis is to implement successful programmes or instruments in order to secure green infrastructure and low impact development in order to manage stormwater more sustainably.

According to Rose, dissatisfaction with the current existing policies as discussed earlier in this Literature Review is the primary driver for policy change. The decision to seek lessons elsewhere for sustainable stormwater solutions may be attributed to Metro Vancouver's regional requirement for municipalities to create their own Integrated Stormwater Management Plans, but the real driver for change can be traced to the macro level in terms of a paradigm shift or a change in societal values.

Rose centers his arguments for the suitability of policy transfer around two main questions: first, is it desirable, and second, is it practical? (Rose, 1991, p. 24). Rose discusses desirability as the legitimate domain of elected officials in that it is up to the representative of the citizens to articulate those desires. Without delving into a political discussion on whether or not politicians actually set out to advocate for the desires of their citizens, there should be an evaluation of whether the programme that is hoped to be transferred is desirable, or whether it aligns with the values of the citizens or residents of the location which will be the recipient. Rose cites an example of a shift in values of the American people that resulted in a demand to eradicate poverty in the 1960s (Rose, 1991, p. 12). He points out that the need for anti-poverty programmes was not a result of an increase in poverty but a change in paradigms or social construct of how poverty is viewed.

Peter May in his article, “Policy Learning and Failure” discusses that failure often happens when a jurisdiction does not incorporate all three types of learning. He describes the three types of learning and notes that the most successful learning occurs when there is evidence of instrumental, social, and political learning. Instrumental learning consists of new understanding about the viability of policy instruments or implementation designs, and recognizes the limitations of policy instruments or implementation approaches (May, 1992, p. 335). May notes that social learning consists of a new or reaffirmed social construction of a policy by the policy elites of a given policy domain. This approach mainly focuses on how society views a problem with the policy. This ties into how poverty was viewed by American society in the 1960s, and how the administration at the time chose to implement policy to align with the ever changing social view. Finally, political learning mostly consists of strategies to advocate for policy ideas, in other words, is it politically feasible? Some topics are increasingly contentious from a political standpoint, and political feasibility addresses whether a policy can be successfully adopted given the current political climate.

The social and political desirability of sustainable stormwater solutions can be tied to the emergence of environment on the agenda of national politics in many countries. Rose notes that this emergence is reflected in the rapid transnational transmission of expert ideas and information (Rose, 1991, p. 17). The desirability of the instrument of policy change is evidenced in the results of the implementation of the policy in another jurisdiction, and therefore, in order to determine if positive lessons can be drawn, the results of the policy in a different jurisdiction must be favorable.

To summarize, in order to determine whether a policy can be successfully transferred, the first question of its desirability whether it be social, political or instrumental must be answered. Based on my evaluation of the literature from Peter May's article, the answer to all three questions should be 'yes' in order to determine whether lessons can be drawn successfully.

The second aspect of suitability lies with the practicality of the policy or programme in question when determining whether it can be imported into a recipient jurisdiction. Rose discusses how technical feasibility is often taken for granted in certain abstract theories of social science where programmes that operate logically in a theoretical model are assumed to be applicable anywhere. This assumption can lead to difficulties in the application of programmes or policy in recipient jurisdictions due to the abstract nature of the theory. In contrast, theories based on other sciences such as engineering sciences in effect can be applicable anywhere. He cites the example of a car motor that can be exported anywhere in the world with modifications made to meet the unique needs of recipient jurisdictions (Rose, 1991, p. 25). I will draw on this to note that the Green Streets Design Manual implemented by the City of Philadelphia is practical, technically feasible, and can be applied locally at the District of North Vancouver because it is in essence based on engineering and environmental science which is less abstract than theories based on social sciences.

The other factors that determine the success or failure of policy transfer can be drawn from the successes noted by the City of Philadelphia in implementing the BID model which was imported from Toronto, but then transformed and improved to the point that the recipient locale became the exemplar. Hoyt attributes some of this success to the network of policy experts and leaders and to the wherewithal of the municipality. This brings us to the next evaluative factor in our framework, and that is whether the resources are available to implement policy change. The consensus of many of the authors within the literature reviewed is that lesson-drawing and policy transfer requires time and resources. The lack of resources could result in the limited ability to research what works well in other jurisdictions. These resources would allow municipalities to hire experts in the field to seek out programmes in jurisdictions that have been successful and to evaluate the reliability of the information being received. For a policy transfer to be successful and to draw positive lessons, the recipient organization will need to have sufficient resources of time, economy, and talent.

This brings us to the next factor in determining whether a policy can be successfully transferred: the availability and reliability of information received and learned. Harold Wolman and Ed Page in their article, “Policy Transfer among Local Governments: An Information-Theory Approach” discusses how information is received, evaluated and utilized. Their study focused on how local officials in the United Kingdom drew lessons or learned from experiences of other local authorities in the area of urban regeneration. The study drew an interesting conclusion, in that the sources of information were informal networks or conversations with friends in other locations or jurisdictions. Their study also found that most local authorities only looked to their counterparts in other areas to determine how to receive funding as they are all reliant on central government funding (Wolman & Page, 2002, p. 485). While this form of policy learning or transfer is technically voluntary, it almost takes on a somewhat coerced nature as the agent of change is not dissatisfaction with existing policy, or an exogenous crisis, but the source of change lies with the need for funding. Parallels can be drawn to coerced policy transfer required by governments providing aid to developing countries, however, the analogies are not exact, as local governments here are looking to improve their competitive edge in terms of funding.

The study also notes resources as a limitation, which is why the local authorities chose to look locally for ideas. The authors note that the urban regeneration partnerships have limited time and funds to engage in elaborate searches, and that locally based examples offered information that was readily available (Wolman & Page, 2002, p. 488). This can be relayed back to our note that having the resources and wherewithal are important in order to complete the necessary research for successful policy transfer and lesson-drawing, and the lack thereof can result in limited sources of information.

The study also discusses the lack of evaluation of information received from sources, in this case, the informal networks of local authorities. The legitimacy and value of the information received is focused around the source of the information rather than the information itself. In essence, if they trust the source of the information, not much else is done to independently evaluate the information itself (Wolman & Page, 2002, p. 494).

Mark Evans and Jonathan Davies in their article, “Understanding Policy Transfer: A multi- level, multi-disciplinary perspective” highlight the importance of elite and cognitive mobilization, and of the evaluation of information in their 12 step process of policy transfer. They describe the stage of elite and cognitive mobilization as the stage in which the agent of change, will be expected to provide detailed information about programmes elsewhere which have addressed a similar problem (Evans & Davies, 1999, p. 378). This step basically addresses the accessibility of information, where the less accessible the information, the less likely the agent or the seeker of new policy or programmes will able to provide detailed information of successful results in another jurisdiction.

Evans and Davies also note that evaluation is important, not just to ensure the information is reliable but in order to determine what exactly will be transferred. In most situations, programmes cannot be exact copies, and the second model of policy transfer known as emulation would occur. Evaluation of the programme in question will allow recipients to determine what, or how much of the donor programme they are going to import or implement, and to what degree (Evans & Davies, 1999, p. 379).

The last factor or tenet of our framework is to determine whether any constraints exists that would result in us not being able to draw lessons or transfer policy or programmes from one place to another. Doing an honest evaluation of the constraints identified in Sections 2.3 and 2.4 of this Literature Review will be the deciding factor in determining whether a policy being used currently in one location can be used in another. If any constraints exist, a detailed review of mitigation strategies should be employed to determine whether any of these risks of failure can be reduced to an acceptable level before moving forward with drafting proposals or developing models around which the new programme or policy can be designed.

To summarize, the conceptual framework I have developed in this section consists of five main factors. The first factor is whether the programme or policy in question is desirable. The second is whether the programme or policy is practical. The third is whether the recipient jurisdiction hoping to draw positive lessons has sufficient resources to complete research and evaluate the information. The fourth is whether the information acquired is accessible and reliable. The last factor in determining whether a programme or policy can be transferred is to evaluate existing or potential constraints that could result in failure to transfer policy.

Chapter 3. Methodology

For this thesis, I gathered and interpreted data found within engineering reports, journal articles, municipal design guidelines, council reports, and literature on policy transfer. Within the Literature Review section of this thesis, I developed my own conceptual framework in order to evaluate whether the City of Philadelphia's Green Streets Design Guideline could be successfully transferred to the District of North Vancouver. I have also conducted key informant interviews to highlight challenges associated with improperly managing stormwater. The Data and Analysis section discussed in Chapter 4 of this thesis describes several green infrastructure and low impact development strategies that, if implemented correctly, could help provide sustainable stormwater management solutions within cities. Within Chapter 4 of this thesis, several technical and maintenance considerations are highlighted that should be considered before implementing certain green infrastructure, or low impact development solutions.

The research conducted, and the findings reported within this thesis have been guided through seven in-person interviews with engineers, landscape architects, civil designers, and environmental consultants. The sampling strategy used for this thesis was convenience sampling, and the interview participants were chosen based on their professional experience, and their knowledge in the fields of sustainable stormwater management, civil design, civil construction, infrastructure maintenance, and creative urban design. In addition to the factors noted above, participants were chosen based on their availability and their willingness to participate in the study.

3.1.1. The Interview Process

After receiving ethics approval for my study, I conducted seven interviews with engineers, planners, designers, consultants, and environmental control officers. All interviewees I approached agreed to participate in my study; however, participants requested to remain anonymous before participating. As most of my participants are still actively practicing their fields of work, many had concerns with sharing challenges, or negative experiences with me if they felt that they could be identified. To respect the anonymity of my participants within the discussion section of this thesis, all participants were assigned numerical values from one to seven. Using numerical values allowed me to differentiate the information provided by my informants from the information gathered through my research without compromising the identity of my participants.

During the interview process, my goal was to create an environment where participants felt comfortable sharing both their positive and negative experiences with me. Respecting my participants' requests to remain anonymous helped create trust during the interview process, and once participants knew that they would not be named or identified personally, they were more willing to share their challenging experiences with me.

Participants for my study were chosen based on their experience and knowledge in the fields of sustainable stormwater management, civil design, civil construction, infrastructure maintenance, and creative urban design. Specifically, participants interviewed held jobs as managers, engineers, planners, municipal workers, environmental professionals, designers, and consultants. All interviews were conducted in a one-on-one format with only myself and the participant present. As stormwater management is a very technical topic, selecting participants based on their knowledge and experience was necessary. Many of my participants were not comfortable being audio, or video recorded during the interviews, and therefore, no audio, or video recordings were taken during the interview process. Notes were taken by hand as I interviewed my participants, and once I had included the information within my research paper, all notes were shredded in a confidential shredder to protect the privacy of all participants.

For the interviews, I created a verbal questionnaire with carefully considered questions that could be answered in approximately 15-20 minutes. All interviews were conducted in a semi-structured format between April 2019 and September 2019. None of the participants involved in the interview process reported to me professionally, or worked for me in any way, and there were no apparent conflict of interest issues that resulted from the interview process. I carefully considered the logical flow, structure, and order of my questions to ensure that all questions asked invited participants to open up and tell a story. None of the questions included in my interview were written to elicit a one word "yes" or "no" answer from my participants. Conducting in-person semi-formal interviews was the most appropriate means of gathering information on the topic I have chosen. Surveys, or written questionnaires were not appropriate for my research because on the technical nature of this study. I strongly believed that my participants were more likely to open up and share their experiences with me in a comfortable semi-formal in-person interview, rather than a written survey, or a written questionnaire.

The interviews were conducted in coffee shops, and meeting rooms in municipal offices, and all interviews lasted approximately 15-30 minutes in total. At the end of each interview I asked my participants if there were any other individuals that they would recommend I speak to regarding my research topic. Very few participants provided me with additional contacts; however, for the purposes of this thesis, I believed that conducting seven interviews allowed me to gain a strong understanding of my topic while still allowing me to meet my time constraints.

3.1.2. Municipal Documents

Since this thesis primarily focuses on how municipalities can sustainably manage stormwater runoff, I have included a number of municipal documents and municipal design guidelines in my research. Table 1 lists the municipal documents reviewed and used within this thesis. Municipal documents were made publicly available through each municipality's official website. I have included documents and design manuals that are relevant to this thesis and offer innovative solutions regarding sustainable stormwater management. All documents were stored and cited using the Zortero citation software.

Document Name	**Organization**	**Year Received or Released**
Streetscape Manual	City of Guelph	2014
Green Streets Design Manual	City of Philadelphia	2014
Wastewater Treatment Plant Bypasses	City of Toronto	2017

Country Lanes Demonstration Project	City of Vancouver	2002
Integrated Rainwater Management Plan	City of Vancouver	2016
Greenest City Action Plan	City of Vancouver	2020
Stormwater Utility	City of Victoria	2016
Study of the Impacts of Climate Change on Precipitation and Stormwater Management	Greater Vancouver Sewerage and Drainage District	2018
Integrated Liquid Waste and Resource Management - A Liquid Waste Management Plan	Metro Vancouver	2010
A Homeowner's Guide to Stormwater Management	Metro Vancouver	2019
District of North Vancouver - Council Workshop 2017	The District of North Vancouver	2017
DNV Climate Change Adaptation Strategy	The District of North Vancouver	2017
Lynn Valley Town Centre Public Realm and Design Guidelines	The District of North Vancouver	2015

Table 1: List of municipal documents reviewed and their sources

3.1.3. **Policy Transfer Framework**

This thesis also uses a policy transfer framework to test ideas about policy learning and policy transfer. I have developed the conceptual framework outlined in Section 2.5 of this thesis to emphasize findings of what worked to advance stormwater management innovations in other municipalities such as the City of Philadelphia, and where municipalities such as the District of North Vancouver can draw lessons in the pursuit of similar innovations.

My Literature Review uses the following articles listed in Table 2 to develop a conceptual framework and extracts key ideas and concepts by which policy gets transferred from one jurisdiction to another.

Article	**Author(s)**	**Year Received or Released**
The Lessons of Learning: Reconciling Theories of Policy Learning and Policy Change	Colin J Bennett and Michael Howlett	1992
Policy Learning and Failure	Peter J. May	1992
What is Lesson-Drawing?	Richard Rose	1991
Who Learns What from Whom: A Review of the Policy Transfer Literature	David Dolowitz and David Marsh	1996
Policy Transfer Among Local Governments: An Information-Theory Approach	Harold Wolman and Ed Page	2002

At the Interface Between Theory and Practice – Policy Transfer and Lesson-Drawing	Mark Evans	2006
Importing Ideas: The Transnational Transfer of Urban Revitalization Policy	Lorlene Hoyt	2006
Understanding Policy Transfer: A Multi-level, Multi-disciplinary Perspective	Mark Evans and Jonathan Davies	1999

Table 2: List of policy transfer literature documents reviewed and their sources

The conceptual framework developed through the literature review using the articles listed in Table 2 is used when analyzing results in Chapter 6 of this thesis. The analysis performed in Chapter 6 discusses whether lesson-drawing is possible from municipalities such as the City of Philadelphia that are considered exemplars in sustainable stormwater management and examines whether programmes that have been successful in other jurisdictions can be implemented locally.

Chapter 4. Data and Analysis

The Data and Analysis section of this thesis will highlight several green infrastructure and low impact development strategies and technologies that should be considered within the urban environment in appropriate circumstances. Notable considerations for each solution are cited within each section. It is important to note that some of the natural stormwater management solutions included within this section are newer technologies, and long-term performance measures still being studied by researchers today. This thesis will not report on the performance measures for some the newer technologies because of this reason. Performance measures, and relevant technical details are included and cited for bio swales, porous asphalt surfaces, and green roof systems, because these low impact development strategies are more commonly used today, and because these strategies have been studied and well documented by researchers.

In 2014, the City of Philadelphia created a comprehensive green streets design manual which showcased many newer, progressive natural stormwater management technologies that utilized green infrastructure to manage runoff more sustainably within the city. Today Philadelphia is the first city in the United States to attempt a largely green approach to managing stormwater, and the city is recognized as a leader in transitioning to green infrastructure (Fitzgerald & Laufer, 2017, p. 256). The City of Philadelphia also received the 2015 National Planning Excellence Award for the implementation of their Green City, Clean Waters Plan which seeks to reduce stormwater pollution through the use of green infrastructure (American Planning Association, 2015). The goal of their design manual was to suggest safe, sustainable, efficient, and attractive ways to manage stormwater in the hope of achieving a cleaner and greener watershed. Philadelphia's Green City Clean Water Program is currently tackling the pollution and flooding issues within the city by adding green infrastructure solutions to manage approximately 10,000 acres of existing impervious surface. More specifically, the City of Philadelphia has approximately 2,575 miles of streets, which accounts for approximately 30% of the impervious area within the city, and engineers have chosen to implement green infrastructure strategies to manage stormwater, and to minimize the amount of pollutants that reach downstream waterways during rain events (City of Philadelphia, 2014, p. 5).

The city’s water commissioner Howard Neukrug stated, “As we witness the effects of climate change causing storms of greater frequency and severity, the green infrastructure we build on our streets is an added safeguard that can help mitigate flash flooding during such events” (City of Philadelphia, 2014, p. 5). It is important to understand that this design manual does not prioritize stormwater management over the functionality or usability of roads or corridors, and this is a reason why this thesis has chosen to incorporate solutions suggested in this guideline within Data and Analysis sections below. For example, the green infrastructure solutions suggested are designed to manage urban runoff while simultaneously considering the walkability, usability, and the aesthetic appeal of the street. Vegetated bump-outs are suggested within the design manual to manage runoff, while simultaneously improving pedestrian and bicycle safety; and stormwater tree trenches and planters are specified to manage urban stormwater while also serving to create lush, attractive streetscapes within the city.

The information reported within this chapter of the thesis was collected by using scholarly articles, journal articles, news reports, engineering reports, policy documents, and design guidelines. The information included within this entire study was specifically chosen to provide the reader with a substantial background on some of the major issues associated with improperly managed stormwater, and some of the more serious consequences that this can have on the urban environment if left unchecked. Throughout this thesis, my research also delves deeply into the importance of managing stormwater sustainably today by shifting away from overreliance on traditional piped conveyance systems, and rather focusing on low impact development, and green infrastructure strategies instead. Several practical examples of low impact development and green infrastructure will be highlighted within this section of this thesis. This has been done in an effort to highlight specific design solutions, to encourage and inspire future planners, engineers, and designers to consider mimicking nature in urban environments, and creating sustainable stormwater management opportunities where possible. The examples provided in this thesis are not an exhaustive list of all green infrastructure and low impact development solutions. New innovative solutions emerge as technology changes, and this thesis has chosen to focus on some of the more common and practically used green infrastructure solutions in urban areas.

Where possible, local Canadian examples have been highlighted and included within my research; however, this thesis does not focus on Canadian issues alone since the improper management of stormwater creates issues that all urbanized countries should address. I have chosen to focus my research on the significant issues associated with improperly managing stormwater, and while many examples included are not local, this was intentionally done in an effort to provide the reader with the best possible background on the topic, and to create the strongest possible case to encourage readers to reconsider traditional stormwater management solutions, and instead focus on mimicking nature in urban environments.

This research outlines many noteworthy considerations that planners, engineers, and designers should take into account before implementing sustainable stormwater management solutions. At the most fundamental level, sustainability should always be considered; however, this thesis outlines many operational considerations that factor into which solution is ultimately chosen. Planners, engineers, and designers are encouraged to consider factors such as: site conditions, costs, budgets, operation, maintenance, and spatial considerations before selecting a specific green infrastructure or low impact design solutions.

Downstream conditions also need to be evaluated because sites draining into sensitive watersheds may need to consider more stringent stormwater management solutions that deal with water quality, quantity, and the rate of discharge into these sensitive receiving areas. This thesis focuses only on sustainable, practical stormwater management solutions that seek to mimic nature within the urban environments.

4.1. What is Low Impact Development (LID)?

Low impact development (LID) strategies encourage the use of small scale stormwater controls, distributed across the city to mimic the pre-development hydrological regimes of watersheds (Eckart et al., 2017, p. 413). The goals of LIDs are to minimize impervious surfaces, reduce native vegetation loss, and significantly reduce stormwater runoff by simulating nature in urban environments. This is typically achieved through infiltrating, filtering, storing, evaporating, and detaining stormwater runoff close to its source. This evolution in stormwater management practice promotes the management of rainwater close to where it falls, and the use of rainwater as a resource.

Low impact development can provide resilience against flooding when combined with pre-existing stormwater infrastructure. If implemented correctly, LIDs can reduce the volume of stormwater runoff, delay or divert stormwater from entering overstressed and ageing stormwater infrastructure and provide added resilience against flooding in extreme rain events (Eckart et al., 2017, p. 414). Planners and engineers at the District of North Vancouver have seen that low impact development can provide a significant reduction in stormwater volume if implemented correctly. It is important to understand that methods for urban stormwater management need to evolve to meet the increased demands resulting from urbanization and climate change, and one way of achieving sustainable stormwater management today is through the use of low impact development controls (Eckart et al., 2017, p. 414).

Microbial contamination in urban stormwater is considered to be one of the most widespread and challenging water quality issues for developed countries (Peng et al., 2016, p. 1). If implemented correctly through best management practices (BMP), low impact development can restore pre-urban hydrology by harvesting and treating urban runoff. The term best management practice is used in Canada and the United States to describe a type of water pollution control. Within the context of stormwater management, best management practices generally refer to principle control or treatment techniques. Low impact development can be used to remove many contaminants and pathogens in storm runoff. Storm biofilters are an example of one specific type of LID BMP. Biofilters are vegetated media filters, and these systems are also known as bioretention, or rain gardens. In cities today, biofilters are becoming increasingly popular because of their multiple co-benefits such as improved hydrology, improved water quality, and aesthetics (Peng et al., 2016, p. 1). Studies have noted that a better understanding of the factors that influence microbial removal in biofilters is required in order to effectively design and implement these systems for microbial water quality improvement.

Constant urbanization and densification has increased the impervious surface areas in our cities, and this has resulted in the following: an increase in volume and rate of stormwater flow, a reduction in the natural infiltration of stormwater back into the ground, negative impacts on urban streams and coastal ecosystems, and pollution and pathogens in our receiving waters and ecosystems which provide significant value as both habitat and recreational resources (Askarizadeh et al., 2015, p. 11275). Every year millions of residents and tourists visit beaches, creeks, lakes, and other water features for recreation purposes, and this generates billions of dollars in economic activity (Pendleton, 2008, p. 166). In the United States, studies have noted that microbial contamination of recreational waters is one of the top causes of surface water quality impairment (Gaffield et al., 2003, p. 1527). Stormwater reuse has recently become an increasingly attractive resource management strategy; however, microbial contamination is problematic when considering water reuse (Pitt et al., 1995, p. 273).

Low impact development can be considered a planning and environmental management practice that primarily focuses on restoring the hydrology of urbanized watersheds to their pre-development condition. These strategies have been receiving a lot of attention recently, and this practice has been increasing used in order to improve human water security by providing a ‘fit-for-purpose’ source of water (Peng et al., 2016, p. 1). Low impact development strategies can also improve the water quality in urban areas, and mitigate hydrological factors that contribute to the urban stream syndrome (Peng et al., 2016, p. 2). The term ‘urban stream syndrome’ is used to describe the consistently observed ecological degradation of streams draining urban areas. Low impact development best management practices generally comprise: bioswales and biofilters, permeable surfaces such as porous asphalt, green roofs, swales and roadside ditches, stormwater bump-outs, green gutters, and storm trees. Biofilter systems are often prioritized in LID implementation, and civil engineers often use these systems within the urban landscape due to their multiple benefits such as infiltration and groundwater recharge, filtration, evapotranspiration, urban heat-island cooling, and visual aesthetics (Grant et al., 2012, p. 682). I will now discuss each of these LID strategies in greater detail.

4.2. Bioswales and Biofilters

In a typical design, biofilters are below-grade areas filled with a designated mix of soil media comprised of sand, mulch, and loam. These areas are vegetated, and underlain with sand or gravel, and include an underdrain and an overflow pipe (Peng et al., 2016, p. 2). The bottoms of the biofilter systems are designed to be either pervious or impervious depending on the site requirements. In certain scenarios, depending on the flow balance and the elevation of the underdrain and overflow pipe, there may be a submerged area at the bottom of the system that could provide additional pollutant removal (Peng et al., 2016, p. 2). During significant rainfall events, a layer of standing water may accumulate in a surficial ponding zone; however, excess water that collects can be released through an overflow drain to mitigate flooding concerns.

A significant benefit of biofilters is their ability to filter polluted water and provide water quality improvement. Due to this efficacy, scientists and engineers have shown an interest in studying these systems to understand the efficiency of biofilter-mediated removal of contaminants within urban stormwater. Studies conducted by Grebel et al. suggested three strategies that engineers can use to increase the removal of contaminants and microbial contaminants commonly found in stormwater. These strategies include: choice of infiltration media, manipulation of system hydraulic behaviour, and a manipulation of redox conditions (Grebel et al., 2013, p. 437).

Peng et al. 2016 evaluated a conceptual model that looked at the removal efficiency of microbial contaminates by biofilters. The centre of their model focused on the processes and mechanisms responsible for removing microbial contaminants. The model also considered the design choices such as filter media, infauna (i.e. the animals living within the sediments of lake and riverbeds), and plants. Operation conditions such as stormwater characteristics, condition of the climate, age of the biofilter, and operation and maintenance were also evaluated. It was noted in their study that all three (process, design choice, and operation conditions) work together and collectively influence the removal efficiency of fecal indicators and pathogens (Peng et al., 2016, p. 3).

The term “transport and fate” describes a process that removes pathogens through physical retention and biological die-off within the biofilter. Transport and fate refers to the physical, biological, and chemical processes that impact the movement of the contaminants from point A to point B, and evaluates how the contaminants may be altered as they are transported. Transport includes the capture of microbial contaminants through filtration and through attachment. By contrast, filtration only refers to capture by size exclusion and the filtration process includes mechanical filtration (i.e. the entrapment at the top of the biofilter media), and straining (i.e. at the narrow pore throats or grain junctions within the media layers). When considering biofilters with median grain diameters that range between 150 to 1000 um, the mechanical filtration process is expected to remove particles >75-100 um (Peng et al., 2016, p. 4) . Particles within this range are mostly fine sand particles and attached microbes. The straining process removes particles 27-100um in diameter at the narrow pore throats, or 0.75-5um at grain junctions (Rippy, 2015, p. 579).

The attachment process occurs when microbes present in the stormwater stick to the biofilter particle grains, and when compared to size exclusion based filtration, the attachment process also plays a crucial role in microbial removal. Attachment provides the ability for the system to capture pollutants of significantly smaller sizes than would be possible with filter media size exclusion alone. Whether or not the microbes successfully stick to the filter grains depends on the *physiochemical properties within suspending fluid* (i.e. pH, the presence of dissolved organics in the storm water, and the ionic strength), *the collector* (i.e. the chemical composition, the electrostatic properties, the diameter, the presence or the absence of biofilm, and absorbed organics), and the microbes (e.g. shape, size, and surface properties) (Peng et al., 2016, p. 4). Attachment also occurs at the particle-air and particle-water interfaces under unsaturated conditions, and this happens when air, water, and solid phases are all present within the biofilter.

The term “fate” is used to describe a biological process such as die-off, or predation where the microbes decay, or are consumed rather than physically captured by the biofilter (Tedoldi et al., 2016, p. 904). There are many abiotic and biotic conditions such as ultraviolet radiation, sunlight, osmotic stress, temperature, moisture content, nutrient availability, that can affect the persistence of microbes in the environment (Rippy, 2015; Shang et al., 2009). Factors such as sunlight, UV exposure, and moisture content were found to be important factors for E. coli survival in biofilter surface layers, whereas the presence of indigenous microbial communities, and temperature were factors that affected E. coli at all biofilter depths (Chandrasena et al., 2014, p. 5400).

Biofilters play an important role in storm water management, and many urban designers choose these systems because of their aesthetic appeal. Although the aesthetics are valued by designers, it is important to note that vegetation plays a key role in regulating soil processes such as nitrogen and carbon cycling, and regulates soil structure, soil stability, and moisture content. Additionally, vegetation allows for many pollutant treatment benefits such as nutrient uptake, controlling erosion, and attenuating and distributing stormwater flow.

Since planting appropriate vegetation changes the soil's physiochemical properties and impacts the soil microbiome, these plants have the potential to remove microbial contaminants through four phases: filtration, attachment, die-off and growth, and predation (Peng et al., 2016, p. 9). In a similar way, vegetation mediated changes in soil moisture content, nutrient availability, and biofilm growth can also affect the removal of microbial contaminants by attachment, die-off and growth, and predation. It is possible that vegetation may also impact microbial removal through its interaction with the soil's fauna (Peng et al., 2016, p. 9).

To date, not enough experimental studies have been conducted to examine and analyze the effects of vegetation on microbial removal within biofilter systems. This is a topic that should be further studied and evaluated since the limited studies to date have shown inconsistent findings. Some studies report higher removal efficiency in unplanted biofilter systems (Kim et al., 2012, p. 123). Other studies have shown improved microbial removal performance within biofilter systems that were planted with specific vegetation such as shrubs of *Leptospermum continentale* and *Melaleuca incana*, and grass types such as *Paspalum conjugatum* and *Buchloe dactyloides* (Peng et al., 2016, p. 10). Certain studies have shown that vegetation within biofilters that assisted in E.coli removal also reduced biofilter infiltration rates (Chandrasena et al., 2014, p. 5400). The results from these studies suggest that that the effects of plants on microbial removal may be indirect through biofilter residence time. These findings by Chandrasena et al. are consistent with the results produced by Parker et al. since Parker reported that fecal indicator bacteria (FIB) removal by biofilters when fully saturated in storm conditions, were lower in vegetated systems that were planted with *Carax Appressa* than non-vegetated systems and this is due to residence time effects. For example, fecal indicator bacteria spent less time in planted bio filters than unplanted biofilters (Peng et al., 2016, p. 10). This is an important finding because vegetation effects on microbial removal are a function of prevailing climate conditions such as storm duration and storm frequency, as well as biofilter design, climate and design related considerations. All factors above need to be taken into consideration when selecting vegetation to be planted within biofilter systems (Chandrasena et al., 2014; Li et al., 2012).

4.2.1. Selecting Vegetation for Biofilter Systems

When selecting specific vegetation to be planted in stormwater biofilter systems, general plant ecological theories can help guide this process. Research has shown evidence that soil regulation by plants can be linked back to different plant resource strategies, such as favouring resource acquisition or resource conservation. Plants with resource acquisition strategies such as *Carax Aprassa* and *Juncus Sp.* have been shown to promote fast nutrient and carbon cycling, which stabilize soil mediums in which they have been planted. These types of plants generally have low leaf density, low root tissue density, longer root length, high root nutrient uptake, low root carbon content, high root and leaf respiration, low root and leaf lifespan, and high photosynthetic capacity (Bardgett et al., 2014; Wright et al., 2004). Research conducted by Reed et al. concluded that plants with root traits consistent with a resource acquisition strategy (i.e. longer roots and deeper rooted depth) removed significantly more phosphate and nitrate from stormwater biofilter influent when compared to resource conservative plants (Read et al., 2009, p. 49) This pattern was not observed when researches evaluated the removal of metals in stormwater runoff, and in the cases where high metal removal was observed, this was attributed to filter media effects, not vegetation. Resource acquisitive plants are more likely to facilitate nutrient removal, whereas resource conservation plants could provide protection against filter media clogging if their thicker root structures promote macropore formation (Le Coustumer et al., 2007; Read et al., 2009).

When designers and engineers are selecting vegetation to be planted in biofilter systems, it is important to understand that plant physiology and plant morphology can change when exposed to adverse conditions. For example, during dry weather events or seasonal droughts, many plants alter their root length and root diameter in an effort to produce longer and thinner root structures to increase their water absorption capacity (Bardgett et al., 2014, p. 696). When starved for water, plants typically assume resource acquisition traits even if the species are classified to be resource conservative.

4.3. Porous Asphalt

Porous asphalt can be an excellent low impact development solution designed to mimic nature in an urban environment by simulating a porous surface though the use of an engineered asphalt product. Porous asphalt pavements systems are not a new technology, these specialized pavement structures have been studied by many researchers in many different contexts and the results have been promising (Berbee et al., 1999; Pagotto et al., 2000; Roseen Robert M. et al., 2012). These engineered permeable surfaces represent a valuable opportunity to harvest, store, and partially treat urban stormwater sustainably, and decrease the volume of stormwater runoff that enters the drainage network.

Due to the large paved surface areas in cities, porous pavements can provide an ideal opportunity for stormwater harvesting and filtering. In principle, the porous asphalt system works in the following way: polluted stormwater infiltrates thought the pavement surface and is then filtered by the pavement layers before it is stored in a tank (Beecham & Myers, 2007; Scholz & Grabowiecki, 2009). Once the stormwater passes though the porous pavement structure, the polluted water is filtrated and significant improvements in water quality can be obtained depending on the types of permeable pavement layers used. After this process, the filtered stormwater can be used for several uses, and potable water can potentially be conserved (Hammes et al., 2018, p. 339).

4.3.1. Potentially Reducing Potable Water Usage by Implementing Porous Asphalt Surfaces

As cities rely more on water conservations strategies, Hammes, Thives and Ghisi conducted a study that assessed the potential of reusing stormwater in sustainable and practical ways (Hammes et al., 2018, p. 338). Research has found that one way of achieving this is to limit the use of potable drinking water as much as possible. The authors make a compelling argument suggesting that in certain cases and for specific uses, potable water can be saved and conserved by using stormwater that has been filtered through porous asphalt pavements located in parking lots. They also argue that stormwater should be used for non-potable purposes such as flushing toilets and urinals.

In their study, two models of porous pavement systems were constructed, and both pavements were installed using porous asphalt mixtures. The porous asphalt surfaces in both pavement surfaces contained different combinations of porous granular layers. After installation, both models were assessed for their filtering capacity and samples of stormwater runoff were collected in a parking lot located near the building where the filtered stormwater was intended to be used. Each of the two models assessed showed that the permeable surface was capable of filtering some pollutants from the stormwater; however, it was noted that additional water treatment was still necessary to obtain the quality of water required for non-potable uses (Hammes et al., 2018, p. 338).

Later in the study one model was analyzed by using it in a parking lot, and the potential for potable water saving was analyzed. The thickness of the temporary stormwater reservoir layer was calculated in order to meet the design rainfall adopted, and the stormwater tank capacity was estimated. The results showed that when using a 45,000 litre stormwater tank, potable water savings of at least 53% could be achieved if filtered stormwater was used to flush toilets and urinals (Hammes et al., 2018, p. 338). This suggests that porous pavement surfaces used in parking lots have the potential of conserving potable water if filtered stormwater runoff is used in buildings.

The authors state that with urban development, the increase of impervious site surface area is becoming more problematic. In many countries around the world, the addition of significant impervious areas are causing tremendous negative impacts on the environment. These negative impacts are related to changes in the hydrological cycle, which in-turn intensifies floods, and this is an especially problematic issue in densely populated cities (Chughtai, Mustafa, and Mumtaz 2014; Jacobson 2011; Miller et al. 2014). Studies suggest that flooding is common in urbanized areas when rain events occur with high intensities, for short periods of time (Hammes et al., 2018, p. 338).

In underdeveloped countries like Brazil, flooding is significantly more problematic and can lead to the loss of critical infrastructure and even human life (Hammes et al., 2018, p. 338). In order to mitigate the negative effects of urbanization, sustainable stormwater management solutions that seek to infiltrate water back into the ground should be considered where practical within the urban landscape.

In certain specific cases, retention reservoirs or stormwater management ponds could be used as a sustainable approach to manage large volumes of water; however, in many circumstances, this strategy often requires dedication of large areas of land that are not always available for this particular use. In densely packed urban areas, an alternate solution to retention reservoirs could be porous asphalt pavement systems. These systems should be designed with drainage layers composed of: concrete or asphalt, with bricks as a surface, and should include granular porous layers that have a high volume of voids and interconnected voids which allow stormwater infiltration, while partially filtering runoff in the process (Hammes et al., 2018, p. 338).

4.3.2. Porous Asphalt and Parking Lots

In busy cities, parking lots are a necessity, and in addition to providing a clean, smooth driving surface, porous asphalt surfaces are also designed to serve as stormwater storage and infiltration systems (Hammes et al., 2018, p. 338). Participant 3 and I discussed that as standard practice, porous asphalt surfaces should only be used in areas such as parking lots and low traffic roads. These engineered surfaces should not be used on major arterial, or collector roads that receive large volumes of vehicle traffic because porous asphalt is not as robust as traditional asphalt and maintenance costs may rise to unacceptable levels.

The inclusion of porous asphalt can be an excellent alternative solution for planners, civil engineers, and designers looking to manage stormwater runoff in an environmentally sustainable way. Porous pavement systems promote infiltration, improve water quality, control peak and total runoff volume, and depending on the type of system, the resulting infiltration can also help recharge groundwater reservoirs (Hansen, 2008; TRCA, 2010; UNHSC, 2014). The potential for runoff reduction using porous pavement systems were measured by many researchers, and results varied from 45% to 99% (James & von Landsdorff, 2003; Kwiatkowski et al., 2007; Legret & Colandini, 1999; Pratt, 1999; Schueler, 1987; TRCA, 2010).

When engineers and planners use porous pavements in their designs, the stormwater infiltration through the pavement layers can be temporarily stored and used, promoting water conservation strategies if implemented appropriately. The storage capacity of these systems can limit overflow discharge and drainage failures by reducing the volume of stormwater runoff that enters the storm network, while simultaneously treating the runoff.

In cities, parking lots can cover significant areas of land, and therefore, these can be ideal places to implement a porous pavement system in an effort to simulate natural permeable ground conditions (Hamzah et al., 2012, p. 3464). Within these engineered systems, the uniformly graded stone reservoir course layer acts as a structural support for the pavement and provides temporary water storage before percolating runoff into the soil. Hamza et al. also stated that a porous parking lot system with a 110cm reservoir course layer was able to withstand approximately 500cm per hour of rainfall intensity (Hamzah et al., 2012).

A permeable asphalt parking surface is comprised of a general porous asphalt mixture poured over a reservoir structure composed of permeable layers for temporary stormwater retention. The reservoir course layers are filled with washed and uniformly graded stones that allow stormwater infiltration, while also providing structural support for the pavement (Hammes et al., 2018, p. 339). The porous pavement layers are designed and established according to the function that they are designed to serve. This function could either be for the temporary storage of stormwater, or for the filtration of some pollutants to improve the water quality of runoff.

4.3.3. **Design Considerations for Porous Asphalt Surfaces**

This section provides high level design considerations for porous asphalt surfaces. Porous asphalt mixtures are designed to have plenty of connected voids (18% – 25%) (Hammes et al., 2018, p. 339). Once air and water circulates through these voids, early oxidation and loss of adhesiveness can occur, and if this happens, the use of modified asphalt is suggested. It should be noted that the aggregate requirements remain the same for conventional mixtures, but their gradation should be uniform, and open graded with few filler content.

The choker course layer, or the stabilizing course, is composed of clean single-sized crushed stone that is smaller than the stones in the reservoir course layer to stabilize the surface for paving equipment (Hammes et al., 2018, p. 339). It is also possible to add an optional filter course layer that can be used to improve the quality of the stormwater. If this option is chosen, a filter blanket layer is required to prevent the material from the filter course from migrating to the reservoir course layer. This layer is often referred to as the “recharge bed” and it consists of clean, single-size crushed large stone with approximately 40% voids which also serves as a structural layer, as well as a temporary reservoir. The geotextile filter fabric allows polluted stormwater to pass through, but prevents the fine materials from the subgrade from migrating to other layers, especially to the reservoir course layer (Hammes et al., 2018, p. 339).

When evaluating the quantity of infiltration that is possible, it is important to note that water infiltration through a porous asphalt surface is dependent on several factors such as: rainfall intensity, rainfall duration, rainfall frequency, evaporation, surface runoff, and the volume of additional stormwater received from other impervious areas (Hammes et al., 2018, p. 339). To collect stormwater for non-potable purposes, generally pipes are engineered and placed at the bottom of the reservoir course layer and spaced between 3 and 8 metres (Hammes et al., 2018, p. 339).

4.3.4. Maintenance Considerations for Porous Asphalt Surfaces

While there are many advantages of using porous asphalt pavement, one disadvantage to note is that these specialized surfaces require periodic maintenance to prevent clogging. Participant 3 noted that if periodic maintenance is not performed regularly, the permeability of these surfaces can become compromised. This is something that owners should consider before implementing these permeable surfaces. Periodic maintenance can be costly, and budgets need to be taken into consideration before installation. As stated earlier in Section 4.3.2, porous surfaces should only be used in parking lots and low traffic roads. In order to maintain the permeability of these surfaces, porous asphalt should be aspirated and pressure washed one to four times a year (Hammes et al., 2018, p. 339).

Although the maintenance of these surfaces could be problematic for some municipalities with low maintenance budgets, porous asphalt surfaces should still be considered for specific projects because of the significant value that they can provide. Many researchers have reported on the presence of organic and inorganic pollutants in road surface stormwater runoff, which can significantly compromise natural ecosystems and cause a loss of biodiversity (Dechesne et al., 2004; Herngren et al., 2005; Kayhanian et al., 2009; Scholz & Grabowiecki, 2009; Soller et al., 2005). Many researchers also argue that porous asphalt surfaces can represent a proactive solution for reducing the volume of polluted runoff in clean bodies of water (Chai Lin et al. 2012; Coleri et al. 2013; Jacobson 2011; Li et al. 2012).

Several studies suggest that channeling stormwater though porous asphalt pavements significantly reduces the amount of hydrocarbons, suspended solids, and metals in the runoff (Barrett Michael E. et al., 1998; Berbee et al., 1999; Chai Lin et al., 2012; Coleri et al., 2013; Li et al., 2012; Roseen Robert M. et al., 2012). It is important for planners, engineers, and designers to understand that the capacity of porous pavement systems to remove pollutants, otherwise known as the “filtering capacity”, is directly related to the ability of the layers allowing appropriate infiltration. In “full infiltration systems”, where stormwater is able to penetrate though all pavement layers, more pollutants are filtered out, and consequently less pollutants are carried and discharged into clean bodies of water.

When standard impervious pavement surfaces are installed in a city, infiltration is not possible, and polluted runoff is consequently channeled and discharged directly into clean bodies of water without filtration or treatment (Abustan et al., 2012, p. 32). Porous asphalt pavement surfaces should be considered in parking lots and on low traffic roads, because these engineered systems infiltrate water, and are capable of capturing pollutants within the surface pores and underlying granular base. The results of studies measuring pollutants after water was filtered by porous asphalt pavement, show reductions greater than 50% for total suspended solids, many metals, and hydrocarbons (Legret & Colandini, 1999; Pagotto et al., 2000; Pratt, 1999).

If municipalities are concerned about maintenance costs and related issues, they could consider securing legal covenants to shift the maintenance obligations from local government to the landowners. This strategy could allow municipalities to enforce this sustainable stormwater management solution, while simultaneously avoiding future maintenance costs.

4.4. Green Roofs

Historically green roofs were used in the Nordic countries; however, in the last 20 years this low impact development strategy has been used in countries all over the world (Versini et al., 2015, p. 562). In recent years, green roofs have gained popularity in developed countries as watershed managers continue to seek to manage rainwater at its source. In countries such as Canada, Brazil, Spain, Korea, the United Kingdom or Japan, the annual green roof covering is estimated to be between 0.1 km^2 and 1 km^2

(Versini et al., 2015, p. 562). France and Germany continue to be leaders in this industry with the annual green roof cover in France estimated at 2 km^2, and the annual green roof cover in Germany estimated at 10 km^2 (Versini et al., 2015, p. 562).

The reason why green roofs have been gaining so much attention recently is because this low impact development solution provides planners, engineers, and designers with the opportunity to revegetate urban areas at the building scale. Roof areas in general are problematic from a stormwater management perspective because these impermeable surfaces represent approximately 40%-50% of the impervious surface area in a city (Versini et al., 2015, p. 562). Green roof systems introduce plants and vegetation on a roof's surface which partially addresses this issue of impermeability, while additionally adding value from an architectural and aesthetic perspective. Studies have reported that green roofs may enhance the aesthetic appeal of buildings while simultaneously reducing heat island effects by increasing evapotranspiration, improving air quality, protecting biodiversity, and sustainably managing urban runoff by absorbing the rainwater that falls on the roof's surface (Santamouris, 2014; Takebayashi & Moriyama, 2007). From a stormwater management perspective, the mitigation and reduction of urban runoff alone is a significant reason to promote the use of green roof systems. In order to mitigate some of the problems associated with urbanization today, green roofs, porous asphalt, rainwater harvesting tanks, and vegetated bioswales can be considered as source control design solutions. These solutions have recently gained relevance over traditional stormwater management approaches which seek to simply direct untreated stormwater into storm drains before discharging the polluted water into receiving clean bodies of water (Delleur, 2003; Petrucci et al., 2013; Ubronas & Jones, 2002). The principle of source control is to develop low impact stormwater management solutions that seek to manage runoff directly at its source. Within urban environments at the building scale, green roofs have the ability to control both the quality and the quantity of urban runoff (Versini et al., 2015, p. 562).

From a water quality perspective, green roof systems infiltrate and filter rainwater, thereby significantly reducing the direct contribution of metals into receiving waters when compared to traditional impervious roof designs (Egodawatta et al., 2009; Gromaire et al., 2011). It should be noted that although green roof systems reduce the levels of metals in runoff, studies have shown that vegetation coverage does increase phosphorous concentration (Versini et al., 2015, p. 563).

From a quantitative perspective, green roof systems have the potential of significantly reducing the volume of storm runoff. The performance of these systems to reduce runoff is dependent on factors such as: the green roof design and configuration, the rainfall intensity, and the antecedent soil moisture conditions that are present within the system at the time of the rainfall event (Versini et al., 2015, p. 563).

Green roof systems are now recognized as important low impact solutions designed specifically to mimic nature in urban environments and manage rainwater directly at the source. The quantitative performance of these systems have been studied by many researchers through direct observation and limited modelling works. In order to assess the performance, small surfaces of experimental green roofs were instrumented to set continuous runoff and precipitation data for short periods of time (generally not exceeding a period of 3 years). The data gathered from these experimental surfaces was then analysed in an effort to study and explain the fluctuations of green roof performance in terms of runoff volume and peak discharge.

4.4.1. Performance of Green Roofs

In Sheffield UK, Stovin et al. conducted a study where a very small 3m^2 test bed comprising of extensive vegetation growing in 80mm of substrate was assessed (Stovin et al., 2012, p. 150). Rainfall runoff monitoring was performed continuously over a period of 29 months, and results indicated that the annual cumulative retention within the system was 50%, and the peak attenuation ranged between 20% and 100% with a median of 59% (Versini et al., 2015, p. 563). In this particular study however, it was not possible to establish any relationship between rainfall retention percentage and the storm characteristics of the antecedent weather variables.

In New Zealand, Voyde et al. instrumented six hydraulically isolated plots that were approximately 10m^2 – 50m^2, and assessed their performance over the period of one year. These six plots differed in two ways, first in their substrate types (i.e. zeolite, pumice, and expanded clay), and second in their depths (i.e. 50mm or 70mm). With the exception of one plot which was designed using coconut coir fibre in the sedum mat, the researchers found no statistically significant difference in the hydrologic performance of these three different substrate types. Over the course of the study, 66% of precipitation was retained within the system and peak flow reductions ranged from 31% to 100% with a median of 93% (Voyde et al., 2010, p. 391). Additionally, the researchers did not notice any statistically significant season related variations when assessing either rainfall, or runoff response. In 2013, over the period of two years additional data was analyzed by Fassman and Simcock within the same site, and similar results were reported when assessing water balance. Interestingly, this study differed from the study conducted by Voyde et al., since notable statistically significant seasonal variation within the system was observed. This was an important difference which highlights the importance of long-term monitoring within green roof systems.

In Genoa, Italy, a significantly larger surface area of $350m^2$ was divided into two plots and covered with green roof. Each plot within this study comprised of 200mm of substrate, and drainage layers that differentiated according to their substrate mix (Palla et al., 2011, p. 767). This study was conducted over a period of 6 months, and the results showed rainwater retention within the system varying between 10% and 100%, with an average of 85%; and a peak flow reduction ranging from 80% to 100%, with an average of 97% (Palla et al., 2011, p. 772).

There are several additional studies that have been conducted assessing the performance of green roof systems, and all studies conclude that the performance of these systems are not linked to one factor only. Researchers agree that there are numerous contributing factors, with several parameters that can have an impact on hydrological response within the system. Factors to consider include: rainfall intensity, rainfall accumulation, the climatic conditions in the area, seasonality, antecedent conditions, and to a lesser extent: the substrate species, the depth of the system, and the slope of the roof. Recent research suggests that rainfall depth appears to be the dominant factor when evaluating retention performance within green roof systems.

When reporting on green roof systems, most researchers to date have focused on conducting studies that reproduce observed runoff at the experimented roof scale in order to extrapolate the impact of green roof systems at the urban catchment scale (Versini et al., 2015, p. 564). Currently studies and research is lacking when attempting to simulate the hydrological response of green roofs by using adapted models; however, it should be noted that green roofs in general require more sophisticated and more frequent maintenance when compared to conventional roofs. Since green roofs are generally located on private property, consideration needs to be given to the capacity and willingness of private property owners to manage and pay for ongoing maintenance activities.

4.5. Swales and Roadside Ditches

In most major cities, roadways are traditionally designed with curbs and gutters on either side of the road to channel stormwater into catch basins and drains before finally conveying the water into the municipal storm network.

During a rain event, a portion of the precipitation is able to infiltrate into the ground through permeable surfaces around the city and this helps replenish groundwater levels. Unfortunately many cities have paved over significant amounts of permeable surfaces to build roadways and other infrastructure, and consequently, the recharge of shallow groundwater resources has been reduced due to the reduction in overall infiltration (Xie et al., 2017, p. 1). When a large volume of rainwater cannot infiltrate into the ground, it flows downhill over paved impervious surfaces taking the path of least resistance, and this is commonly known as overland water runoff, or stormwater runoff. While runoff can be problematic because of associated erosion and pollution problems, runoff also plays an important role in replenishing downstream rivers, lakes, and other bodies of water. In cities, a large number of pollutants are generally introduced onto the road surface from vehicle traffic, commercial activities, industrial activities, and construction, and this pollution is carried away with the stormwater runoff. Improperly managed runoff from road networks can have many negative environmental consequences such as flooding, property damage, erosion, the degradation and pollution of aquatic habitats in streams and rivers, and the deterioration and pollution of water quality (Xie et al., 2017, p. 1).

Before the introduction of curbs and gutters, stormwater runoff was conveyed to receiving waters primarily through a series of swales and ditches. This specific design technique continues to be used in certain rural areas around the world, and in some newly designed urban areas that seek to maintain a rural street aesthetic while simultaneously managing stormwater runoff sustainably (Sustainable Technologies, 2019).

Removing curbs and introducing swales and ditches along the shoulders of roads can represent another excellent example of low impact development that sustainably manages stormwater close to the source by mimicking nature within the urban landscape rather than relying heavily on piped storm systems. Curb-less streets can represent a new approach to thinking, and a completely different way of designing a roadway or corridor. Studies suggest that stormwater drainage should be changed from traditional systems into sustainable stormwater management solutions that mainly rely on permeability, water storage, and drainage (Xie et al., 2017, p. 10).

4.5.1. The Advantages of Using Swales and Ditches Rather Than Standard Curbs and Gutters

When curbs are removed and swales are introduced, a major benefit of this strategy is that rainwater is now able to filter and infiltrate into the ground as it is conveyed along the swale, resulting in lower volumes of runoff and fewer pollutants in downstream bodies of water. Although swales are generally used to supplement or replace traditional curbs and gutters within an urban setting, swales can also be used for erosion control in agricultural lands (Ahiablame et al., 2012, p. 4261). As a new ecological measure, swales can be used to collect road-surface runoff, and where appropriate (on local and low volume roads), this design strategy could replace part of the stormwater pipe network (Xie et al., 2017, p. 2). In the District of North Vancouver, swales and ditches are always considered within civil designs in appropriate areas; however, planners and engineers are mindful of the costs that must be considered if this infrastructure is placed on municipal land. With the goal of minimizing the adverse impacts that result from too much impervious land cover, LID strategies such as swales and ditches seek to manage runoff naturally by infiltrating polluted water back into the ground, rather than piping stormwater and discharging it into downstream watercourses. This type of low impact development approach to land development can be thought of as “urban retrofitting” which is designed to operate within the context of preserving a healthy watershed (Sohn et al., 2017, p. 1871). Grass swales, if maintained appropriately, can do an excellent job of absorbing water, and plant roots pre-treat polluted water flowing through the system thereby reducing the overall contamination of the water (Xie et al., 2017, p. 2).

The terms “swales” and “roadside ditches” are generally used interchangeably even though there are important differences between the two systems. Engineered swales are constructed as shallow channels with gently sloping sides, designed to manage surface runoff, filter out pollutants, and increase rainwater infiltration. The major distinction between swales and ditches is that swales are intended for both conveyance and treatment, while ditches are designed primarily for conveyance only. Swales are often more costly to install, and they generally require more maintenance than ditches (Sustainable Technologies, 2019). Grass swales and permeable pavement are important low impact design solutions that have been extensively studied.

Research suggests that swales and ditches represent an excellent low impact development strategy, and if used appropriately within a city on low volume roads and where soil conditions are acceptable, these systems can have many advantages when compared to traditional curbs and gutters because they are able to infiltrate water back into the ground (Jackisch & Weiler, 2017, p. 143). Within an urban setting, consideration also needs to be given to the safety implications of ditches and swales in areas frequented by vulnerable groups such as children, the elderly, or disabled people.

Xie et al. conducted a study and found that when the rainfall repetition period ranged from 0.33a to 10a (where “a” refers to the rainfall repetition period), the reduction rate of total runoff within areas that implemented swales and permeable pavement ranged from 27.5% to 100%, and the reduction rate of peak flows ranged from 15.9% to 100% (Xie et al., 2017, p. 10). Other studies have also reported similar findings suggesting that the implementation of swales can significantly reduce runoff and reduce peak flow rates.

4.6. Stormwater Bump-Outs

A stormwater bump-out planter is a type of bioretention facility that is usually located within a city street right-of-way (Urban Green Infrastructure Guidelines, 2017b, p. 30). Stormwater bump-outs are another example of green infrastructure designed to introduce pockets of nature within a largely impervious urban environment. Bump-outs are generally considered to be ideal locations for green infrastructure initiatives (City of Guelph, 2014, p. 63). These areas are simply landscaped and planted curb extensions, or curb bulges designed to sustainably manage stormwater runoff from the roadway and the adjacent sidewalk. The most common type of bump-out is achieved by setting the top of the planting media within the bump-out at a lower elevation than the gutter elevation on the street and then connecting the bump-out to one more inlets (City of Philadelphia, 2014, p. 26). Designing bump-outs in this specific way allows stormwater from the street to flow directly into the system, and stormwater from the sidewalk to flow into the bump-out from the surface. The width of a bump-out is generally designed to be approximately 2.0m to 2.4m wide, which slightly less than the width of a typical parking lane (City of Guelph, 2014, p. 63).

Bump-outs capture and infiltrate stormwater within the planted areas, and also within the subsurface stone beds located at the bottom of these systems. Planted vegetation grown within the bump-out absorbs some of the stormwater through the root systems, and the remaining water is then temporarily stored within the curb bulge until the water either infiltrates into the ground, or drains back into the storm sewer through the connected inlets. In mid-block bump-outs, any overflow of stormwater typically exits the system though an opening on the downstream side, directing flow into a nearby storm sewer (City of Philadelphia, 2014, p. 26).

4.6.1. Benefits of Bump-Outs

There are numerous benefits to installing stormwater bump-outs within a city. First, from a stormwater management perspective, these bump-outs offer the ability to filter polluted water through the planting medium which improves the water quality of runoff (City of Philadelphia, 2014, p. 26). Bump-outs also sustainably manage stormwater close to the source by introducing natural permeable planted surfaces within a largely impervious urban environment. This is preferable to traditional stormwater management techniques which allows large volumes of runoff to pick up pollutants as it travels over roads and sidewalks before the untreated water is conveyed though the storm network and finally discharged into downstream receiving areas. Bump-outs also provide additional benefits such as providing a physical safety buffer between pedestrians and the street, reducing the crossing distances for pedestrians when bump-outs are placed at intersections, encouraging lower vehicle speeds by narrowing the street, and providing aesthetic improvements within the city by adding greenery in addition to street trees and roadside planting (Meenar, 2019, p. 15).

4.6.2. Considerations and Maintenance Obligations of Bump-Outs

Although bump-outs are advantageous from a stormwater management perspective, there are several factors that need to be taken into consideration before implementing this type of green infrastructure within the city. First, bump-outs should ideally be located in areas that do not receive deleterious amounts of de-icing salts, since too much exposure to salt can compromise the growth of plant life and vegetation within the system (Urban Green Infrastructure Guidelines, 2017b, p. 31). Planners and engineers at the District of North Vancouver are mindful that creating bump-outs change the existing curb lines and drainage patterns on the street. Before installation and construction, all designs should be evaluated to ensure that drainage paths are not negatively impacted. Sizing and locating storm bump-outs often require civil engineers to determine the extent of all upstream areas which could ultimately drain into the planter. More specifically, the size of a bump-out usually depends greatly on the size of the upstream area that drains into it (Urban Green Infrastructure Guidelines, 2017b, p. 31). As such, siting stormwater bump-outs in upstream areas may not be as effective as siting them mid-block or downstream so that these planters are able to intercept and manage runoff more effectively. Bump-outs can also create a loss of street parking, reduce street widths, and impact vehicle turning radii. When planting vegetation within these green systems, sight lines should always be considered to avoid the creation of blind spots for turning vehicles. When placing bump-outs near intersections, designers should ensure that pedestrians have a clear maneuvering passage, and unimpeded sight lines (City of Philadelphia, 2014, p. 26). Careful consideration needs to be made to ensure that storm bump-outs do not encroach into cycling areas (City of Guelph, 2014, p. 64). Mid-block bump outs also require careful consideration to ensure that these installed systems do not encourage unsafe and unwanted mid-block pedestrian crossings. Ideal locations for bump-outs include an integration within pedestrian seating areas or within close proximity to transit shelters (City of Philadelphia, 2014, p. 26).

In addition to the considerations noted above, cities and all parties concerned should consider the maintenance requirements of these green infrastructure systems. Bump-outs routinely require general landscape maintenance such as watering (especially during dry weather periods which tend to occur more frequently with climate change), trimming to ensure that safe sight lines are maintained, and litter removal.

4.7. Green Gutters

When curb lines are necessary on a roadway, green gutters can be an excellent design solution for planners and engineers who seek to manage road runoff sustainably (City of Philadelphia, 2014, p. 34). Green gutters are constructed as narrow, shallow, landscaped strips along the curb line of a road. It is important to understand that green gutters need to be well vegetated in order to maximize the functionality and aesthetic appeal of these systems (Urban Green Infrastructure Guidelines, 2017a, p. 44). Green gutters are typically planted with sedums or low growing grass, and these systems are designed to attenuate, filter and infiltrate runoff (Schollen & Company & Urban Forest Innovations, 2017, p. 34). In order to intercept the flow of stormwater, the top of the planting media within the green gutter system is set at a lower elevation than the gutter line on the street. Designing the system in this way allows the runoff from the street and the adjacent sidewalk to flow directly into the green gutter system where stormwater can be managed appropriately. In certain circumstances when concrete curbs are absolutely necessary, an elevated curb with cut out openings along its length can be used along the road side of the green gutter. These cut outs are installed to allow stormwater runoff to flow from the roadway into the green system. If desirable or required, green gutters can be designed to infiltrate and flow into an existing adjacent storm sewer piped system. In “flow-through” green gutters, the overflow of stormwater runoff can be sent to storm networks by either an underdrain which is installed and tied into the existing storm drain, or as shallow concentrated flow that is conveyed downstream to existing inlets (City of Philadelphia, 2014, p. 34). When compared to regular impervious concrete curb and gutter infrastructure, green gutters can be preferable from a stormwater management perspective if used in the correct circumstances. These low impact development systems attenuate the flow of runoff, provide storage of water, and in some cases can promote evapotranspiration and infiltration.

4.7.1. Benefits of Green Gutters

From a stormwater management perspective, green gutters can provide an excellent opportunity to manage runoff sustainably though the use of green infrastructure rather than impervious curbs and pipes. Green gutters have the ability to infiltrate, attenuate, detain, evaporate, and clean some pollutants from storm runoff (City of

Philadelphia, 2014, p. 34). Other benefits of this green infrastructure include beautifying the city by providing an area within the right-of way for planting vegetation in an otherwise concrete and asphalt urban environment (Urban Green Infrastructure Guidelines, 2017a, p. 45). In situations when an elevated street side curb is used, green gutters can also be used as safety measure by creating a physical buffer between pedestrians on the sidewalk and vehicle traffic on the roadway. Unlike stormwater bump-outs, green gutters do not require encroachments into sidewalk areas, a factor which can be beneficial for cities as they look to secure wider sidewalks for pedestrian movement. Clear, wide, and unobstructed sidewalks are beneficial for visually impaired individuals, people on wheelchairs, and individuals with strollers.

4.7.2. Considerations and Maintenance Obligations of Green Gutters

Similar to stormwater bump-outs, careful consideration needs to be given to existing on-street parking before installing green gutters to manage runoff. This type of green infrastructure generally requires dedicated areas within the corridor, and if on-street parking is removed in order to accommodate this type of infrastructure, community engagement may be required to ensure that businesses and residents are not significantly impacted by the loss of street parking. Similarly, if existing road widths and sidewalks are narrow, this type of green infrastructure may not be appropriate to implement as installation will further narrow the drivable surface. Landscape materials and planting within green gutters should also be designed to consider and accommodate the direct impact of gutter flow velocity (City of Philadelphia, 2014, p. 34). Careful consideration should also be given to ensure that the edge treatment of the green gutter systems is appropriately and safely designed, and this is especially true when green gutters are placed adjacent to bike lanes, or highly used pedestrian sidewalks. Ideally, green gutters should be designed and planned to accommodate any necessary pedestrian traffic, and the overall length of these gutters should be determined to ensure smooth pedestrian flow (Urban Green Infrastructure Guidelines, 2017a, p. 45). This means that the edge treatment of the gutters should be designed to prevent cyclists and pedestrians from stepping into or encroaching into the planted area. Similar to storm bump-outs, green gutters should not be installed in areas that receive deleterious amounts of de-icing salt, since too much exposure to salt can compromise vegetation growth within the system (Urban Green Infrastructure Guidelines, 2017a, p. 45). When cycle lanes exist or are contemplated within the road corridor, it is important to ensure that green gutters do not encroach into bike lanes, since this can create a safety hazard for cyclists. Generally, green gutters are most appropriately sited and installed on roads with wide shoulders, and no street parking. This type of green infrastructure may not be appropriate on certain roads with high volumes of pedestrian activity.

The maintenance requirements for green gutters are fairly standard, these systems require routine landscape maintenance, and periodic waste and litter removal. Although a variety of vegetation can potentially thrive in green gutter systems, generally design guidelines recommend that planners and engineers plant native grass within these areas in order to help ensure a neat, clean, and visually appealing aesthetic (Urban Green Infrastructure Guidelines, 2017a, p. 44).

4.8. Storm Trees

When sidewalks widths are relatively wide, specialized tree pits planted with a single storm tree can be considered to manage stormwater runoff more sustainably. This type of green infrastructure manages road runoff by setting the top of the planting media within the tree pit at a lower elevation than the street's gutter elevation, and subsequently connecting the tree pit to an inlet allowing stormwater to enter the pit (City of Philadelphia, 2014, p. 28). Runoff from the adjacent sidewalk can also flow directly into the tree pit from the sidewalk surface. A portion of the stormwater directed into this green infrastructure system will infiltrate within the planting media and be utilized by the tree, and the remaining water will drain via a connection to the piped storm network. During heavy rainfall events, or if the storm tree system is at capacity, bypasses are installed within the system to allow stormwater runoff to enter the downstream storm drain directly. When space is readily available, several tree pits can be installed in a series to maximize stormwater infiltration and treatment within these green systems.

4.8.1. Benefits of Storm Trees

In addition to sustainably managing stormwater, storm trees can provide several benefits within an urban environment if implemented correctly. A significant benefit of a storm tree is that it requires a relatively small footprint when compared to other green infrastructure solutions such as stormwater planters, bioswales, green roofs, and green gutters. Within the city, spatial availability should always be considered when designing or installing new infrastructure. A storm tree can be accommodated and installed on relatively constrained sites, and this green infrastructure solution can also be accommodated in challenging urban areas with steep topographic changes in grade (City of Philadelphia, 2014, p. 28). Strom trees can also be used for beautification purposes by adding street trees and greenery within the urban landscape. Studies have stated that urban trees have a positive impact on the quality of human life, and apart from the aesthetic appeal, street trees can provide a wide range of benefits and services such as producing oxygen, providing shade from the sun, reducing heat island effect, and providing wildlife habitat within a city (Schollen & Company & Urban Forest Innovations, 2017, p. 15). In an effort to reintroduce nature back into the urban environment, landscape architects can stagger and install storm trees in-between street furnishings and infrastructure such as benches, hydrants, streetlights and street signage. In cities such as Toronto which seek to increase tree canopy cover by 40%, storm trees should be considered because of the multiple benefits they provide, and because they have the ability to manage runoff more naturally and sustainably (Schollen & Company & Urban Forest Innovations, 2017, p. 22). In addition to providing shade on busy sidewalk areas, street trees can also create a physical separation between pedestrians on the sidewalk and traffic on the roadway. Within the urban corridor, and especially in spatially confined areas, municipal design guidelines can be written to secure the use of this green infrastructure solution when new sites redevelop, thereby reducing some of the reliance and burden placed on the piped storm network.

4.8.2. Considerations and Maintenance Obligations for Storm Trees

Although storm trees provide a natural solution to managing polluted runoff, consideration should be given anytime non-traversable intrusions are designed and constructed within the sidewalk right of way. As a general rule, a storm tree can intrude into a walking zone with a maximum width of two feet, a maximum length of five feet, and a minimum spacing between trees of thirty feet (City of Philadelphia, 2014, p. 28). Planted storm trees require routine tree maintenance such as pruning and litter removal.

Additional consideration needs to be given anytime trees are required to be planted over existing underground infrastructure as their root systems can damage or cause defects to subsurface pipes or conduit (Schollen & Company & Urban Forest

Innovations, 2017, p. 25) . If possible, planners, engineers, and designers should avoid planting trees over existing underground infrastructure if other planting areas exist.

Sewer defects are generally classified into two main groups: structural defects, and operational defects. Structural defects include damage caused by internal corrosion, or longitudinal cracking, whereas operational defects include root intrusion, or the infiltration of groundwater into a leaky sewer. The consequences and impacts of damaged infrastructure, or sewer flow blockages depend on the type of infrastructure that is impacted. For example, root intrusion into a sanitary sewer generally poses a more serious hazard because this could cause partial or total flow blockages within the pipe, or leakage of sewage which could cause contaminated ground conditions within surrounding soils (Kuliczkowska & Parka, 2017, p. 1). Interference between trees and sewer systems are likely to occur in older systems, and factors that contribute to damage include: aging pipes with joints, shallow pipe installation depths, small-dimension pipes, and fast-growing tree species (Randrup Thomas B. et al., 2001, p. 1). Roots are reported to cause more than 50% of all sewer blockages within a city, and the costs associated with root removal from sewers can be substantial (Randrup Thomas B. et al., 2001, p. 1). For cities managing smaller dimension pipes, root intrusion is common, and root removal either annually or bi-annually is generally required (Randrup Thomas B. et al., 2001, p. 1).

Cities incur major costs annually to renew and replace existing pipe infrastructure and these costs can sometimes be accelerated because of root intrusion from street trees. Major breaks and blockages in pipes appear to occur more frequently with older infrastructure, and while collapse repair costs are generally greater than new construction costs (i.e. to entirely replace underground infrastructure), it should be noted that the cost of root removal could be as much as one-sixth of the cost of fully replacing or renewing a pipe that is damaged or blocked due to root intrusion (Randrup Thomas B. et al., 2001, p. 1). Given the cost implications of root intrusion and the damage that this can cause on underground infrastructure, designers and landscape architects should be discouraged from placing trees above underground pipes when possible.

In addition to the problems associated with root intrusion, tree roots can also damage sidewalk panels, streets, and parking lots if street trees are installed incorrectly. Participant 1 discussed the problems associated with tree roots damaging public road infrastructure and noted that this was primarily due to tree roots growing under pavement structures, upheaving and displacing sidewalks, curbs, and adjacent roads. When sidewalks and adjacent roadways are upheaved by tree roots, this can create tripping hazards for pedestrians, and safety hazards within bike lanes due to the uneven travel surface. Participant 1 also noted that pavement failures directly associated with root growth can include: upheaval, vaulting, faulting, displacement, cracking, and breaking. The main form of damage occurs as tree roots increase in size causing differential movement of the pavement surface, and cracking which begins to form after a period of time. The extent of cracking and pavement movement can depend on factors such as the elasticity and thickness of the pavement structure, which is why damage to asphalt surfaces is generally greater than damage to concrete sidewalk panels (Giuliani et al., 2017, p. 1). Curbs are less likely to be damaged than sidewalks because streets are generally built with more compacted base materials causing them to be less aerated (i.e. suboptimal for root growth) when compared to the base material under sidewalks (Giuliani et al., 2017, p. 1). In order to safeguard roots from spreading and upheaving sidewalks and adjacent roadways, root barriers can be considered when trees are planted within the urban environment. Root barriers are made of corrosion-resistant metals, plastic, or fiberglass and they are used to line the perimeter of the planting area. Once a tree is planted, the root system spreads until it reaches the barrier wall, and once this happens the roots continue to grow deeper rather than spreading outside the planting area and damaging adjacent sidewalks or pavements.

4.8.3. **Stormwater Tree Trench**

When sidewalk widths are wide enough to accommodate boulevard areas, stormwater tree trenches can be considered. A stormwater tree trench is a subsurface trench that is installed within a sidewalk area with a series of street trees planted along a section, or total length of the trench. Runoff that is directed into this system enters the subsurface trench and is stored within the empty spaces between stones, or within the storage media in the trench where it is used to water the trees before slowly infiltrating through the bottom of the trench (City of Philadelphia, 2014, p. 30). The surface above the trench surrounding the street trees is set at the same elevation as the boulevard, and surrounding sidewalk surfaces. Participant 3 noted that stormwater tree trenches generally require periodic cleaning of inlets and pipes which can amount to more maintenance when compared to a single storm tree system. These planted tree trenches can provide many similar benefits such as adding trees and greenery within the urban environment, however, tree trenches are generally able to manage a larger volume of stormwater runoff when compared to single storm trees (City of Philadelphia, 2014, p. 30).

4.9. Policy Recommendations

This thesis discusses that municipalities need to consider implementing Development Servicing Bylaw and policy changes to help municipal staff secure and promote the use of green infrastructure and low impact development on all newly developed lots. Research on this topic concurs that although recent advancements in stormwater best management practices suggest the use of these strategies, policy changes are likely necessary in order to achieve this goal (Lieberherr & Green, 2018, p. 1). It is important to remember that policy formulation is about choosing a type of policy instrument that can be used to address a particular policy problem while considering both technical and political feasibility (Howlett et al., 2009, p. 135). This was discussed within the Literature Review section of this thesis and has formed part of the conceptual framework that I have developed. Unfortunately many municipalities today, including the District of North Vancouver, lack clear bylaw and policy requirements that specifically promote the use of green infrastructure and low impact development on all newly developed lots. This can be problematic because city staff often need to rely on policies and bylaws when negotiating infrastructure requirements with external consultants and designers. Furthermore, the successful implementation of green infrastructure can require access to private property in order to build well-functioning natural engineered stormwater management systems (Lieberherr & Green, 2018, p. 1).

In the absence of bylaw and policy requirements, gaining access to private property can become challenging for municipal staff. The City of Philadelphia also faced similar challenges, since the municipality did not have access to land other than public streets, and therefore they determined that building public and private partnerships was critical when implementing their green infrastructure solutions within the city (American Planning Association, 2015). Learning from the City of Philadelphia, municipalities can consider using a participatory approach to green infrastructure in an effort to engage citizens early to help them understand why portions of their private property may be required to facilitate sustainable stormwater management solutions.

The success of green infrastructure implementation in the City of Philadelphia relied on the support and participation from the public. Residents were encouraged to identify green infrastructure opportunities within their neighbourhoods. The city also provided homeowners with free rain barrels and homeowner grants for the development of rain gardens, downspout planters, and de-paving projects. The City of Philadelphia recognized that the success of their green infrastructure program depended on the buy-in from their community and their city partners (American Planning Association, 2015). The city teamed up with various organizations to identify opportunities for stormwater management in capital and transportation projects. This reaffirms the importance of engaging the general public to ensure that citizens understand why municipal staff may require access to their private land. City staff should be equipped with the necessary policy instruments so that they can engage citizens and extend the coverage of green infrastructure by decentralizing the application across larger areas of the city (Lieberherr & Green, 2018, p. 2). If done correctly, this means that city planners and engineers could consider the correct implementation of green infrastructure solutions without having to be constrained unduly by public and private property boundaries.

Municipalities should consider including clear requirements within their Development Servicing Bylaw that requires all newly developed lots to maximize the use of green infrastructure and low impact development solutions within their designs. Studies have shown that policies which are able to levy stormwater fees or indirect subsidies can also be very effective when promoting and securing low impact development within a city (Chang et al., 2018, p. 367). In this thesis I have demonstrated through my research that relying only on the conventional management of stormwater is not sustainable, and today's urban environment requires a new approach to managing runoff more naturally without the overreliance on curbs, gutters, and piped conveyance systems. Understanding that new policy requirements could create challenges, incentives may need to be provided particularly when city staff may need to access private property in order to implement natural stormwater management solutions. This thesis will now recommend two specific policy options that could be implemented by municipalities to help secure green infrastructure and low impact development in cities.

4.9.1. **Rebates and Cost Share Programs**

Rebates and cost share programs could be one possible solution to help motivate private property owners, since this strategy can represent a direct economic incentive to purchase and install green infrastructure on private property. These types of programs could be used to subsidize the costs associated with the engineering design and the construction of eligible green infrastructure solutions, such as rain gardens or green roofs. This strategy could also be particularly useful for municipalities that seek to promote natural stormwater management solutions for newly built single-family homes. This thesis will not discuss specific dollar values for these financial incentive strategies, or how costs will be managed by governments, since this topic can become very complicated and would likely warrant an entirely new study. However, as a recent example, the Seattle Public Utilities Department currently provides large rebates, on average approximately $4,800, for rain garden installation on private property, and these rebates are calculated and based on the square footage of a roof area that is designed and devoted to rain gardens (Lieberherr & Green, 2018, p. 6). Research suggests that these rebates and cost sharing programs are a popular policy mechanism in the United States, and these programs can be relatively straightforward to administer; however, it should be noted that in a survey of the rebate program, participants in Washington D.C stated that they preferred upfront payment assistance rather than a delayed rebate program (Lieberherr & Green, 2018, p. 6).

4.9.2. **Stormwater User Fees**

A stormwater user fee could represent another policy consideration that municipalities could consider to encourage developers and landowners to include low impact development solutions on their sites. Local governments in Victoria and Halifax have implemented stormwater user fees, and charges are based on a “fee for service” basis. The general idea is that stormwater user fees would be charged based on a fair allocation of benefits and costs, and the total fees collected would make the utility self-sufficient so that little or no subsidy is required from the property tax base (City of Vancouver, 2016, p. 66).

Currently in Metro Vancouver, six municipalities have implemented stormwater user fees, and these municipalities include: Langley, Pitt Meadows, Richmond, Surrey, West Vancouver, and White Rock (O'Neill & Cairns, 2016, p. 40). Of these six municipalities, most municipalities have chosen to implement a flat rate stormwater user fee structure. A flat rate charge for stormwater user fees can be desirable because of the simplicity of its administration, however, a major disadvantage of the flat rate method is that charges are not based on any measurement of a site's impermeability. Therefore, if a flat rate stormwater user fee is implemented, landowners may not be incentivized to reduce the amount of impermeable surface areas on their land since doing so does not directly reduce their stormwater user fee charges.

In the City of Victoria, the primary reason for creating a stormwater user fee was to provide an incentive for stormwater pollution control which would be financed by changes on untreated impervious areas (City of Vancouver, 2016, p. 66). Participant 4 and I discussed that while it may be more administratively time consuming for municipalities to implement, a stormwater user fee based on impervious area calculations are a more accurate and a more fair method of determining stormwater charges since each property is assessed individually. The impervious method of fee calculation does not assume that all properties are the same, and it rewards properties that have maintained more natural stormwater assets with lower utility charges (O'Neill & Cairns, 2016, p. 45). The City of Victoria is the closest municipality in proximity to the District of North Vancouver which bases stormwater user fees on an impervious area calculation method.

In Victoria, property owners receive an annual stormwater utility bill, and charges are based on the specific characteristics of their lots. Stormwater user fees can also be understood as "user pay" fees since landowners are charged based on their use of the municipal storm system. In Victoria, landowners who manage more runoff sustainably on their land get charged less on their utility bills than landowners who direct the majority of their runoff into the municipal storm network. This is because in Victoria, stormwater user fees are calculated based on the specific characteristics of a landowner's property including: the amount of impervious area that exists on their lot, municipal street cleaning requirements (charges are calculated based on property frontage), the impact that the property has on the stormwater system (based on the property type and determined by BC assessment, e.g. low density residential, multifamily residential, institutional, or commercial, industrial), and finally any programs that exist to clean stormwater before it leaves the property (City of Victoria, 2016). By structuring fees in this way, stormwater utility fees could give landowners an economic incentive to reduce the runoff from their private properties (Environmental Commissioner of Ontario, 2016, p. 20). As regulatory pressures increase to reduce the environmental impacts of stormwater, many municipalities are now looking for a dedicated source of funding for stormwater management programs, such as a public stormwater user fee (Lieberherr & Green, 2018, p. 7).

Stormwater user fees are imposed on private property owners to help cover the costs of stormwater management in the city. These costs typically include the operation, monitoring, and maintenance of green stormwater infrastructure. It is important to understand that all stormwater policies should primarily seek to encourage and support the development of green cities by promoting and securing low impact development and discouraging the further degradation of our environment by continuing to build grey impervious surfaces and structures (Chang et al., 2018, p. 381). Many governments around the world charge stormwater fees to help secure adequate funding, in an effort to protect the environment and become more resilient to climate change, and in the United States, more than 1,600 municipalities have implemented stormwater fees, and English and Welsh utilities also currently charge a surface water drainage fee (Environmental Commissioner of Ontario, 2016, p. 20).

A policy option to implement a stormwater fee can create many municipal benefits since these fees can provide municipalities with a dedicated funding source that allows them to engage in long-range planning, preventative maintenance, and large scale capital improvements if necessary (Environmental Commissioner of Ontario, 2016, p. 21). A well-designed stormwater fee can also create a tangible cost that must be paid for unsustainable stormwater management, and this could directly incentivize developers and property owners to manage their runoff more sustainably. As stated earlier, this incentive can be created if the stormwater fee is based on the extent of impermeable surface area on a site. If the policy is created in this way, landowners may be encouraged to reduce the extent of impermeable surface areas on their sites, and consequently their runoff by implementing green infrastructure or low impact development solutions to manage stormwater more naturally and sustainably. At the District of North Vancouver, planners and engineers have discussed that stormwater fees based on runoff are generally considered to be a more equitable way to finance stormwater management within a city because this fee structure creates a polluter pay principle. If structured in this way, this means that property owners who create the most runoff, pay the largest amount for their proportional share.

4.9.3. Potential Challenges Associated with Stormwater User Fees Based On Impervious Area Calculations

One of the challenges that municipalities could face when implementing an impervious area method of calculating stormwater user fees is that it entails a significant amount of time and resources when compared to a more simplistic flat rate fee method. This is because the process of assessing impervious areas on each lot requires GIS and aerial imagery, and this is more technically complicated and time consuming when compared to a flat rate fee structure. GIS aerial imagery must also be updated on a regular basis to ensure that the accuracy is maintained for all properties (O'Neill & Cairns, 2016, p. 45).

Additionally, for economically constrained households, a new stormwater fee could impose an additional financial burden on utility bills, and residents may be opposed to the implementation of a new fee. In response to this concern, municipalities could consider phasing the stormwater fee over a period of time and reduce or eliminate the fee for certain classes of properties, or for certain property owners who cannot afford to pay the fee. In this particular case, municipalities could also work with such property owners to help them create low cost solutions, where possible, to managing their runoff more appropriately.

Finally, there may be significant administrative costs that municipalities could face when implementing a new stormwater fee. Research suggests that costs can be reduced if groups of municipalities work together to share the costs, or if the province reduced administrative costs by providing a sample bylaw, templates, or guidance documents (Environmental Commissioner of Ontario, 2016, p. 21). Although municipalities may face challenges initially, policy changes are often necessary as cities look to secure more sustainable stormwater management solutions through the implementation of green infrastructure and low impact development.

Chapter 5. Discussion: Providing Sustainable Stormwater Management Solutions within a City: Challenges, Opportunities, and Considerations

With urbanization, population growth, and climate change on the rise, this thesis asks the question: how can planners, engineers, and civil designers achieve sustainable stormwater management solutions within cities? The research conducted on this topic suggests that one way of achieving this goal is by mimicking nature in urban environments through the implementation of low impact development, and green infrastructure solutions. The research cited in this paper has suggested that traditional stormwater management solutions that rely only on piped conveyance networks (i.e. storm services, and storm mains) can be problematic. This is because conventional stormwater management solutions that rely on piped conveyance networks alone can pose many problems such as flooding, property damage, erosion, pollution of downstream environments, and losses of aquatic biodiversity. This thesis discusses that low impact development and green infrastructure solutions can be used to design and construct natural processes back into the urban environment in an effort to manage stormwater more sustainably. Chapter 6 of this thesis evaluates whether lessons can be drawn from cities such as the City of Philadelphia who have been successful in implementing these low impact development and green infrastructure solutions.

As stated in the methodology section of this thesis, all participants that were interviewed were professionals who had significant experience in civil engineering, project management, civil construction, and sustainable stormwater management solutions. They were able to share personal stories that highlighted both the positive and negative aspects of introducing these green initiatives. They also shared challenges that prevented them from implementing these green infrastructure solutions in the past. All participants unanimously agreed that mimicking nature within urban environments was an excellent sustainable stormwater management strategy, and many of them spoke about the importance of capturing and managing stormwater close to the source, which is consistent with the literature findings reported within this thesis.

Three of my interview participants (participants 3, 4, and 7) discussed the importance of Development Servicing Bylaw requirements when securing low impact development, and green infrastructure solutions. Implementing sustainable stormwater management strategies can have cost implications, and in order to successfully achieve compliance, strict, clear, and enforceable bylaw requirements are often necessary. More specifically, this can be achieved through requirements in Development Servicing Bylaws that allow municipalities to require green infrastructure and low impact development solutions to be implemented on all newly developed lots. The discussion section of this thesis focuses on newly developed single-family lots, and newly developed non-single-family lots. The term "non-single family" refers to all newly constructed development sites excluding single-family lots and single-family subdivisions. I focus on new development projects because municipalities are often able to provide input into the designs of newly developed sites, and this is often when the most change can be implemented at the site level. The discussion section will also discuss permeable laneways (i.e. country lanes), since this is a sustainable design strategy which can allow municipalities to increase the permeability of rear laneways within a city.

5.1. New Single-Family Developments

One major issue that was flagged three different times during the interview process by participants 3, 4, and 7 was the importance of securing sustainable stormwater management solutions for all newly developed single-family lots. These interview participants expressed similar concerns stating that municipalities usually focus the majority of their attention on larger developments, and less emphasis is placed on securing sustainable stormwater management solutions for newly built single-family homes. In the Lower Mainland, many municipal design guidelines and Engineering Servicing Bylaws specifically regulate stormwater management criteria for non-single family developments such as low rise, high rise, multi-family, institutional, and industrial developments, as well as newly built single-family subdivisions. This can be problematic because the majority of new developments in municipalities such as the District of North Vancouver comprise of newly built single-family homes which are not subdivided. More specifically, through discussions with the District's Building Department, it was noted that from January 2018 to August 2020, the District of North Vancouver issued 101 building permits for new single-family homes which were not subdivided, only 2 building permits for single-family homes which were subdivided, and only 25 building permits for non-single family developments.

I was told by participant 3 that many municipalities in the Lower Mainland have seen a trend where smaller, modestly sized older single-family homes are bought by developers for land value alone. Once the lot has been purchased, developers often demolish the older homes, and rebuild the largest possible single-family dwellings allowed in the city's zoning bylaw. If left unchecked, this practice can be problematic for many reasons. First, when single-family lots redevelop in this way, the overall permeability of the land generally decreases significantly. This is largely because the new building footprint generally increases tremendously in size. In addition to an increase in the building's footprint, many zoning bylaws specify height restrictions for single-family homes, while simultaneously exempting certain floor space areas in basements from maximum floor space ratio (FSR) calculations if basements are constructed deep enough underground. As developers seek to maximize the dwelling size in order to sell their newly developed lots for the largest possible premiums, they generally excavate and construct the deepest possible basements allowed with very little consideration or understanding of subsurface groundwater tables. Deep basements can alter natural groundwater tables and compromise the natural water balance within an area. Additionally, driveways, parking structures, parking pads, and even coach houses are generally maximized wherever possible on single-family lots. This can result in post-development land that is significantly less permeable when compared to pre-development conditions. Through engineering servicing bylaws, many municipalities impose restrictions on the width of driveway aprons; however, this is usually only regulated on public municipal land. At the District of North Vancouver, for single-family lots which are not subdivided, driveway aprons are usually limited to 4.5 meters and 6 meters in width on municipal land, but once the driveway crosses into private property, the municipality does not regulate a maximum paving width on-site.

Participant 3 stressed the importance of remembering that the problems mentioned above are usually seen on newly constructed single-family lots, and not on single-family subdivisions, or non-single family redevelopments. While this may seem like a subtle difference, single-family subdivisions often require rezoning, and through the rezoning process, municipalities are able to regulate and specify more stringent development requirements, including sustainable stormwater management strategies. In cases when lots are sufficiently large, and rezoning is not required to subdivide a single-family parcel, municipalities can still secure sustainable designs since granting subdivision is usually a discretionary process, and this allows city staff to dictate certain terms of re-development.

Both participants 3 and 4 expressed concerns that when reviewing single-family subdivision applications, many municipalities require applicants to ensure that vehicles can exit the lot in a forward-facing manner. This requirement is often secured though development planning policies, or through bylaw requirements aimed to provide the driver with improved site-lines to reduce the probability of collisions while exiting the lot and merging with traffic on the roadway. While this strategy can promote safer driving conditions for vehicles exiting the lot, this requirement often increases the extent of impervious front yard paving on newly subdivided single-family lots. Vehicle turning movements must be submitted to the city for review before subdivision designs can be accepted by municipal engineers and planners. Participant 3 also stated that in order to accommodate the turning movements required for a vehicle to exit a lot in a forward-facing manner, civil designers often specify large concrete or asphalt driveways. In order to reduce impervious paving, both participants 3 and 4 suggested that subdivision designers could consider shared driveways; however, it was noted that there are challenges with using this approach, and more often than not, if vehicles are required to exit lots in a forward-facing manner, both driveway and front yard paving are generally maximized. Participant 3 and I discussed that shared driveways can further exacerbate the extent of front yard paving, since now multiple homeowners, owning multiple vehicles, must use and share one paved drivable surface.

5.1.1. Increasing the Permeability of Driveways on Newly Developed Single-Family Lots

There are solutions that designers can use to reduce the impermeability of a driveway surface; however, these strategies are generally only implementable on subdivision applications when the municipality has some degree of control over the design. For example, participant 3 stated that driveways do not need to be constructed from asphalt or concrete alone, although these are generally the materials used for driveway construction today. Instead, it was noted that driveways could be built using permeable pavers that allow rainwater to infiltrate back into the ground.

Participant 3 did note however that permeable pavers require regular maintenance since the crevices between the pavers tend to accumulate silt, which can block rainwater from infiltrating into the ground. If driveways are constructed from permeable pavers, it was discussed that future homeowners should be informed about the maintenance requirements, otherwise, once the pavers become clogged, these permeable driveways are not much better in managing rainwater than their concrete or asphalt counterparts. Participant 3 also stated that when used on driveways, permeable pavers are generally less robust than concrete or asphalt driveway surfaces. If installed incorrectly, using improper compaction methods, permeable pavers can heave and move, and this can create an unappealing visual aesthetic for homeowners, as well as a potential tripping hazard. It was discussed that constant and routine vehicle turning movements on these types of driveway surfaces can also further exacerbate the heaving and movement of pavers if they are installed incorrectly.

Participant 7 suggested that designers could also potentially use split driveways as an alternate design solution to manage stormwater on driveway surfaces. Split driveways are designed to only pave the wheel path that vehicles use, and they allow stormwater to soak into the middle permeable strip which is usually planted with grass. These types of driveways are usually constructed specifically with the intention of reducing impermeable paved surfaces, and to allow for rainwater infiltration. Unfortunately, participant 7 discussed that split driveways also require more maintenance when compared to standard concrete or asphalt driveways, and maintenance can be more frequent if vehicles drive over the permeable grass surfaces. Another issue with split driveways is that they are not designed to accommodate vehicle turning movements (i.e. vehicles are required to drive on the paved wheel path only), and therefore, it was discussed that split driveways may not be an appropriate design solution for municipalities that seek to have vehicles exit lots in a forward-facing manner.

5.1.2. Potential Municipal Challenges Associated with Securing Green Infrastructure and Low Impact Development Solutions for All Newly Developed Single-Family Lots

All participants I interviewed agreed with the importance of securing sustainable stormwater management solutions on all newly developed single-family lots; however, participants working for local municipalities raised concerns about how this could be achieved. I was told by participant 1 that most municipalities in the Lower Mainland do not currently have requirements in their development servicing bylaws that allow staff to impose stormwater management requirements on single-family developers. Given the importance of this issue, some municipalities are considering including additional low impact development and green infrastructure requirements in their engineering servicing bylaws in future years. No participants interviewed were able to comment on specific dates, or general timelines when these bylaw changes would be made, and this is likely because implementing these changes could be challenging.

Participant 3 suggested that the reason municipalities may be cautious about implementing the required bylaw changes is because historically single-family developers have usually been exempted from any stormwater management requirements. In fact, participant 3 stated that the majority of applications submitted for municipal review today are designed by architects or designers alone, and currently most single-family developers do not have civil engineering consultants retained on their projects. Most municipalities have engineering bylaws that require all rainwater on site to be managed within private property boundaries. This means that developers and homeowners cannot divert rainwater from their properties onto neighbouring lots, or onto municipal land. While this requirement is important, it does not require developers or homeowners to consider sustainable stormwater management solutions, rather it simply allows landowners to direct rainwater from their sites into the municipal storm system. In certain cases when single-family lots are located at lower elevations than municipal storm mains on the road, gravity sewer connections are not possible, and sump pumps are required to pump water into the municipal storm network. Participants 1, 3, and 7 suggested that it can become problematic when the majority of single-family lots pump and discharge the majority of the water collected from their sites into municipal storm mains. It was discussed that this can create capacity issues for municipal storm infrastructure, flooding during significant rain events, erosion in downstream receiving environments, and negative impacts to aquatic life. The issues listed here are consistent with the findings I reported and cited within the Chapter 1 of this thesis. Additionally, participant 3 highlighted that if sump pumps fail, homeowners could risk flooding and property damage.

Given the challenges associated with improperly managed stormwater on single-family lots, all interview participants discussed the use of low impact development and green infrastructure solutions to help tackle this issue. Some examples of green infrastructure and low impact development that could be considered on single-family lots include bio swales, rain gardens, detention ponds, and permeable surfaces such as permeable pavers and split driveways. Additionally, participant 7 suggested that single-family landowners should be encouraged to disconnect their roof leaders from draining into the municipal storm network, and rather seek to manage as much water on-site as possible. This strategy to disconnect roof leaders is consistent with the guidance provided by Metro Vancouver in their Homeowner's Guide to Stormwater Management which was discussed in Section 1.3 of this thesis. It was also discussed that there are cost implications associated with implementing these green infrastructure and low impact development solutions, and many municipalities including the District of North Vancouver could initially expect pushback from the development community if bylaws required the use of sustainable stormwater management solutions on all newly developed single-family lots.

As discussed in Section 4.9.2 of this thesis, if municipalities were to draw lessons from the City of Victoria and implement a stormwater user fee based on impervious area calculations, this could incentivize developers to manage stormwater on single-family lots more sustainably. This could be because new homebuyers may be incentivized to purchase these lots due to the ongoing cost savings associated with lower stormwater user fees. If the demand for these new homes becomes sufficient, developers could likely include the costs associated with installing these sustainable stormwater management solutions within the purchase price of the new lots. Additionally, as developer's designs are refined through lessons learned, and as construction becomes more routine, the overall costs for these sustainable solutions on developers could potentially decrease.

5.1.3. **Municipal Staffing Considerations**

Given the volume of single-family new construction applications, another difficulty some smaller municipalities could encounter as a result of these bylaw changes could be a lack of staffing within their engineering departments. Although many municipalities today focus their attention on concentrating density in town center areas and constructing more multi-family dwellings, the volume of applications to build new single-family homes can still remain high. As discussed earlier in Section 5.1, it was noted that from January 2018 to August 2020, the District of North Vancouver issued 101 building permits for new single-family homes, and only 25 building permits for non-single family developments. Currently some municipalities may not be staffed appropriately to meet the demands of this additional workload. Interview participants 3, 4, and 7 suggested that additional municipal engineers and technicians could be required to review the consultants' proposals and ensure that the planned systems meet the new stormwater management criteria outlined in the revised development servicing bylaws. It was discussed that, while this shift to sustainability may require additional staffing, these new technicians and engineers could be hired on a contractual temporary full-time basis. As development is cyclical, this approach to hiring could protect the municipality from being overstaffed if the development industry slowed down, while simultaneously allowing the municipal engineering departments to be appropriately staffed to review and inspect the new stormwater management systems installed on all newly developed single-family lots.

5.1.4. The Water Balance Model – An Online Tool To Demonstrate Sustainable Stormwater Management Solutions On Single-Family Lots

As discussed in Section 4.9 of this thesis, the City of Philadelphia attributed a lot of the success of the implementation of their green infrastructure program to the support that they received from the public. They noted that their successful implementation was a direct result of public support for a more livable and sustainable community, and the City of Philadelphia educated their contractors and also encouraged innovations through design competitions (American Planning Association, 2015).

The lesson we can draw from the City of Philadelphia's recent success is the importance of engaging the public so that they understand why sustainable stormwater management solutions may be required on their lots. More specifically, municipalities can look to online web-based tools to help inform single-family developers on the importance of including low impact development and green infrastructure solutions on newly developed sites. During the interview process, I discussed the topic of engaging the public with all participants. All participants agreed that developers and landowners should understand why improperly managed stormwater is problematic and recognize that there are sustainable solutions that can be implemented to help mitigate the problem. Additionally, participant 1 and participant 3 discussed that the District of North Vancouver is currently in the process of implementing a water balance model, which is a simple web based tool that allows homeowners and developers to interactively view how their properties manage rainwater. The model can also illustrate how different landscaping features can slow, sink, and spread rainwater in an effort to restore the natural water balance of a property after it has been redeveloped. Users of this web based tool are required to create an account from the website and then log in. Online users can either create a brand new project, or revisit existing projects that were saved within their profile.

If a new project is created, the first step users are required to input is the watershed in which their property is located. Interview participant 3 stated that it was important for an educational tool to be easy and user friendly for all end users to operate. In the case of the water balance model, if users are unsure which watershed their properties are located within, they are encouraged to enter their specific address, and the web based tool will provide them with this information. Users are also able to use an interactive map to identify their lots, and within the mapping view they are able to toggle between map view and aerial views to help make this process easier. When users click on the interactive map, an information box appears providing details about the watershed that they are located within, and site specific water balance targets for the lot in question. Once users have identified their properties, and reviewed the watershed sensitivities, they are encouraged to create their project and input some basic site specific information such as the site condition, soil type, depth of excavation, and lot width, depth, and area. Once this step is complete, users are encouraged to add various interactive blocks to the site plan of the property to see how these added features affect the water balance of their property. Within the District's water balance model, there are three block features available. Grey blocks include buildings and hard impervious surfaces that preclude rainwater infiltration and result in water running off into other parts of the property. Blue blocks are included to represent rainwater slow release options such as raingardens, cisterns, and infiltration swales. Within the District's Water Balance Model, each blue block must be connected to a grey block to illustrate that runoff from hard surfaces can be stored and then slowly released back into the ground. Finally, green blocks represent absorbent surfaces such as landscaping, infiltration swales, and permeable paving. These green blocks represent surfaces that can absorb the rainwater that falls on them, but unlike the blue blocks, they do not store additional rainwater that flows from other hard surfaces on-site. Once all this information is included within the model, a stream health gauge is displayed indicating how effectively the specific property is mimicking the natural water balance. Noting this, users of this web-based tool are able to evaluate the performance of their sites, and experiment by adding low impact development and green infrastructure solutions to ensure that their lots are managing rainwater sustainably and naturally. Once this process is complete, users are able to generate a report describing in detail each feature added to the property, and the volume of rainwater that can be naturally managed by each blue or green block. Once this has been done, homeowners and developers are encouraged to print this report and include it within their permit application submissions.

While development servicing bylaw requirements, and policy changes are often necessary to facilitate the implementation of sustainable stormwater management solutions on all newly developed single-family lots, municipalities can draw lessons from the City of Philadelphia's recent succes and promote education through interactive online web based tools such as the water balance model.

5.2. Newly Constructed Non-Single-Family Developments

During the interview process, participants 2, 5, and 6 primarily discussed non-single family developments since these are the types of projects that they most commonly manage in their careers. Within the context of this thesis, the term "non-single-family" refers to all development sites excluding single-family lots and single-family subdivisions. Developments within this category can include multi-family developments, institutions, and even wastewater treatment plants. Participants 2, 5, and 6 stated that generally, in most cities, achieving sustainable stormwater management solutions on non-single-family sites can be less problematic with well-functioning municipal government oversight. This is because municipalities in Metro Vancouver have implemented Official Community Plans, and design guidelines that dictate development requirements on these sites.

Non-single-family development sites are often larger, and more densely developed than single-family lots, and therefore, it was discussed that municipalities generally emphasize a greater focus on securing sustainable solutions when these sites redevelop. While initially it may seem logical for municipalities to invest the majority of their time and effort to ensure that non-single-family sites are redeveloped sustainably, it should be noted that municipalities such as the District of North Vancouver receive significantly more applications to rebuild single-family lots, when compared to non-single-family lots. As noted in Section 5.1 of this thesis, from January 2018 to August 2020, the District of North Vancouver issued 101 single-family redevelopment building permits, and only 25 non-single family redevelopment permits. Noting this significant disparity in new construction permits issued, participant 3 flagged this as being problematic, and suggested that municipalities should focus more attention on newly built single-family lots.

5.2.1. Non-Single-Family Design Guidelines for Redevelopment

Participants 2, 5, and 6 stated that when developers apply to rebuild on non-single-family lots, they are often required to follow strict development servicing bylaw, and design guideline requirements. It was discussed that in Canada, many municipalities have created development hubs, or town centre areas where density, transportation, and amenities are concentrated. In most cases, each of these town centre areas is governed by strict design guidelines that dictate the form and character of the area. Design guidelines generally specify architectural requirements, specific urban landscape features, planting requirements, aesthetic sidewalk designs, ornamental street lighting designs, overhead utility undergrounding requirements, and even public art requirements. Given the problems associated with improperly managed stormwater, many design guidelines today also specify green infrastructure and low impact development solutions for sites located within sensitive watersheds.

For example, in the District of North Vancouver, Bosa Development is currently building a flagship development in the Lynn Valley Town Centre area comprising of condominiums, townhouses, and commercial retail units. This project features six new low rise buildings with over 350 new residential homes, several commercial units, and a grocery store built at grade. Importantly to note for this thesis, this particular site is located within the Hastings Creek Watershed area, which is known to be particularly sensitive to erosion and pollution related issues. In addition to the units built, this development was also responsible for building three new roads named Valley Centre

Avenue, Conifer Street, and Library Lane to create appropriate circulation within the Lynn Valley Town Centre area.

Given the density and impermeability of this future town centre development, and due to the sensitive watershed that it is located within, the developer was required to ensure that the site complied with very specific stormwater management criteria stipulated by the District of North Vancouver. Participant 2 stated that municipalities generally have a greater degree of control with non-single-family developments such as this when compared to new single-family developments. This is because, when developers rebuild, they often request density lifts on the land, and through the rezoning process most municipalities are able to secure offsite upgrades, and infrastructure upgrades for sanitary, storm, and water mains. In this example, the District of North Vancouver was able to highlight the Hastings Creek sensitive watershed issues, and with the help of the Lynn Valley Town Centre Design guidelines and the District's Development Servicing Bylaw requirements, the municipality was able to require Bosa to manage stormwater on their site in an environmentally sustainable way.

5.2.2. **Lynn Valley Town Centre Public Realm and Design Guidelines**

Participant 2 stated that in addition to the new building footprints, the introduction of three new roads added significant impermeable surface areas to the Bosa project, and in an effort to manage this, the Lynn Valley Town Centre Design Guidelines specified landscaped drainage swales, and infiltration areas within the site boundaries. More specifically, the design guideline stated that all pathway surfaces should be sloped to a parallel drainage swale (Ramsay Worden Architects, 2015, p. 12). These guidelines also required the developer to integrate innovative stormwater management measures within the architecture and the design of the public realm. Furthermore, I was told by participant 2 that the developer was required to creatively design green infrastructure solutions that allowed stormwater collected from the roofs of buildings or fixed canopies to infiltrate into rain gardens (Ramsay Worden Architects, 2015, p. 17). The design guideline stated that space permitting, all green infrastructure solutions should be located on private property to reduce maintenance burdens on the municipality (Ramsay Worden Architects, 2015, p. 42). Along residential frontages, the guideline dictated that landscaping should be dominant, and all street trees and vegetation should be combined with rain and stormwater management facilities (Ramsay Worden Architects, 2015, p.

33). This guideline also clearly specified all trees, vegetation, and plant types allowed for raingardens. Sustainable stormwater management features that incorporate green infrastructure solutions, and low impact design strategies are encouraged throughout the design guideline. Participant 2 also stated that this document enabled the municipality to secure sustainable stormwater features within the newly constructed streetscapes within this project. Where constrained street cross-sections could limit the capacity to provide traditional rain gardens, the guideline encouraged developers to focus on capturing and directing rainwater into subsurface French drains (Ramsay Worden Architects, 2015, p. 42). Green infrastructure and low impact development solutions are also encouraged in between buildings, within plaza areas, and within sidewalk areas when space is available.

Although prescriptive design guidelines can help municipalities achieve environmentally sustainable stormwater management solutions, there are some instances when low impact development and green infrastructure solutions may not be practical or achievable. Participants 2, 5, and 6 stated that in many cases sites can be very constrained, and spatial considerations may preclude municipalities from securing certain natural stormwater management solutions. Chapter 4 of this thesis recognizes spatial constraints as an issue, and has cited several low impact development and green infrastructure solutions that can be used in spatially constrained areas. In the case of the Bosa redevelopment example, participant 2 stated that the Lynn Valley Town Centre Design Guideline suggested cisterns, or detention tanks to store rainwater received from roofs. As discussed in Chapter 1 of this thesis, stored water can be used within buildings to flush toilets, thereby saving on potable water usage, or the rainwater could be stored within cisterns for slow release into the ground, or into adjacent municipal storm sewer systems.

5.2.3. Considerations Associated with Over-Reliance on Underground Detention Tanks and Cisterns

During the interview process, when asked, participants 2, 5, and 6 all briefly discussed the potential problems associated with the over-reliance of cisterns or detention tanks. Participant 2 noted that in many cases (especially when sites are spatially constrained) designers specify large cisterns, or detention tanks to store and hold stormwater for slow release into the municipal storm network. While these engineered tanks may be necessary in many cases, participant 2 noted that consultants should try and reduce the overall tank size, and seek to manage rainwater more naturally by mimicking natural processes where possible instead.

For the Bosa development site, given the sensitivity of the Hastings Creek watershed, participant 2 told me that detention tanks were necessary to store and hold rainwater; however, it was noted that the overall tank size could have been somewhat reduced by introducing more swales, or low impact solutions within the project's design. When designing a site from a sustainable stormwater management perspective, participants 2, 5, and 6 all agreed that the primary goal should be to get as much rainwater back into the ground as possible in an effort to manage rainwater naturally at the source whenever possible. The interview participants noted that only when all green infrastructure, and low impact design solutions have been maximized on a site, should the remaining rainwater be managed by underground tanks.

Participant 2 also noted that developers may default to specifying the use of underground tanks within their designs rather than seeking to maximize the use of green infrastructure and low impact development solutions. It was explained that this is usually because these tanks are located underground, where they cannot be seen, and do not occupy valuable above ground surface space on a project site. Detention tanks and cisterns do however occupy subsurface space, which is also valuable, and in certain cases these tanks can conflict spatially with underground parkades. Participant 2 also stated that in many cases (including the Bosa Development example above), detention tanks are constructed from plastic products, and once buried, these plastics can create unknown environmental impacts in the future. In certain cases, detention tanks can also be constructed from concrete, but participants 2, 5, and 6 highlighted that regardless of the material used, these tanks require regular maintenance to ensure that debris and sediment does not clog the system. Given the maintenance requirements, and the future costs associated with this work, it was noted that municipalities generally require detention tanks and cisterns to be located on private property whenever possible. In the case of the Bosa development project in Lynn Valley, participant 2 told me that spatial constraints on the site precluded the developer from constructing all detention tanks on private property, and the entire length of the new road Library Lane was constructed with plastic Graff Eco Block detention tanks below the surface of the road. In cases like this, when detention tanks need to be located under public roads, municipalities can legally shift maintenance requirements onto private landowners. In this particular example, participant 2 told me that the District of North Vancouver secured a statutory right-of-way over Library Lane and shifted maintenance requirements of the subsurface detention tanks to the private landowners.

Although the green infrastructure solutions discussed in this thesis often require routine maintenance, these solutions use a natural approach to managing rainwater, and if used correctly, interview participants agreed that they can help reduce the amount of plastic and concrete products buried within the urban landscape. Participants 2, 5, and 6 suggested that in many cases, a combination of detention storage, and green infrastructure is generally required to manage runoff more sustainably.

5.3. Permeable Lanes: An Environmentally Friendly Lane Design

Country lanes, or permeable lanes, can be an excellent low impact design solution when used appropriately in cities. During the interview process, I met with a former City of Vancouver project manager who oversaw the city's country lane projects in 2003. I was told that the City of Vancouver's Corporate Management Team routinely encourages all city staff to incorporate sustainability into all city operations as a way of doing business. Throughout this thesis, I have demonstrated through my research that urbanization has converted formerly natural, permeable surface areas into impermeable surfaces to build roads, lanes, buildings, and other civil infrastructure. While paved roads are ofen necessary for a city to function appropriately, it is important to note that not all drivable surfaces may need to be paved curb to curb using impervious surfaces. Rather, this section of the thesis discusses the implementation of permeable country lanes in rear laneways when vehicle volumes are low. This alternative lane design approach seeks to engineer natural processes back into the urban environment in an effort to manage rainwater more sustainably.

5.3.1. What are Country Lanes?

In the early 2000's, in an effort to reduce the impervious paved surfaces around the city, the City of Vancouver introduced an alternative environmentally sustainable design solution for rear laneways. I was told by participant 1 that the country lane design was originally inspired by split driveways which were discussed earlier in Section 5.1.1 of this thesis. It was discussed that country lanes represent a different design approach to full width asphalt lane paving, and implementing this design has helped the city ensure that they were taking the correct steps to achieve their goal of reducing environmental impacts and creating a more livable city. Country lanes seek to maximize natural stormwater drainage, infiltration, and filtration, and this design allows rainwater to percolate over vegetated surfaces before infiltrating back into the ground.

In low traffic rear laneways, country lanes are typically designed with two narrow drivable strips designed to support vehicle weight, surrounded by permeable structural grass. These drivable strips are typically constructed from either concrete or asphalt as preferred materials since they are strong, durable surfaces. These drivable strips are required to provide the appropriate structural strength necessary for vehicle traffic in the laneway. Participant 1 stated that it is important to remember that rear lanes must be designed to accommodate not only cars, but also heavily weighted garbage trucks, and other service vehicles that frequently use the lane. The driveable strips are surrounded by a structural component that is 'topsoiled' and then planted with grass. This structural grass component is fitted with a rigid plastic grid that can support vehicle weight, although it was noted that this can be problematic if vehicles continuously drive over the grassy permeable surfaces. The rigid plastic grid also helps prevent soil rutting, and grass roots from being compacted. It was noted by participant 1 that early grass development was important to the success of the constructed project. This is because as grass roots grow into the subgrade, the roots anchor down the structural grass, preventing it from lifting and shifting positions. Since grass growth from seeding techniques can be very slow, I was told by participant 1 that sodding and pre-growing structural grass, or hydro-seeding can also be considered.

In certain situations, the drivable strips can be constructed from either gravel or grass; however, during the interview process, participant 1 and I discussed that this type of surface treatment is not nearly as robust as concrete or asphalt. Drivable surfaces constructed from grass or gravel do not provide a clear visually defined driving strip to direct traffic, gravel is prone to rutting and dust generation, and neither grass nor gravel provide long term durability, which can expose cities to higher long-term maintenance costs. The road bases for country lanes are typically constructed from a mixture of aggregate to provide structural stability, including a soil and sand mixture that allows drainage and provides the soil components required for grass to grow on the surface.

Participant 1 said that careful considerations need to be made at the laneway entrances, and at the driveway connections to homes, since the turning movements of heavy multi-axle vehicles such as garbage trucks, service vehicles, and emergency vehicles can place a lot of stress on these areas of the laneway. In an effort to increase the durability at some of the laneway entrances, participant 1 stated that the City of Vancouver has installed concrete aprons, and permeable pavers within these areas. Permeable pavers were chosen because they are generally considered to be aesthetically pleasing, while simultaneously allowing the City of Vancouver to use a more robust surface that promotes rainwater infiltration.

5.3.2. The Benefits of Permeable Country Lanes

If used appropriately, country lanes can provide a more environmentally friendly, and visually appealing aesthetic alternative to existing gravel and asphalt lanes within a city (City of Vancouver, 2002, p. 2). Constructing rear lanes in this manner can allow cities to reduce impermeable paved surfaces, while simultaneously accommodating vehicle traffic. This alternative approach to laneway design allows rainwater to naturally absorb into the ground, reducing the total volume of water discharged into municipal storm sewers. Managing rainwater and getting it back into the ground as close to the source as possible is an idea that this thesis has continually discussed, since this sustainable approach also helps recharge the groundwater within a city and reduces the peak flows into downstream receiving areas. Participant 1 stated that the vegetated areas within these laneways can also help filter stormwater and can help improve air quality by increasing the local greenspace in the area. It was further discussed that apart from the environmental benefits, these innovative and sustainable laneway designs can be aesthetically pleasing if maintained appropriately, and country lanes can also help with traffic calming by encouraging vehicles to travel at lower speeds. Traffic calming in rear laneways can be especially important for parents if children routinely play in the area.

5.3.3. Cost Considerations for Country Lanes

Participant 1 told me that the country lane demonstration project cost approximately twice as much as a traditional full width asphalt paved lane. This twofold increase in cost was predominantly due to the lack of experience city staff had with these new types of laneway projects. Participant 1 and I discussed that as staff learn from their experiences, and as design and construction become more routine, the overall costs for these laneway projects can be expected to generally decrease. Other reasons for higher costs included: the labour costs to hand-form the concrete drivable strips, the permeable paver driveway connections and costs to install the laneway entrances, broken concrete driveway connections, working with new materials such as structural grass and structural soil, constructing and building the laneway in strips rather than one uniform section, and additional base excavation and placement costs. It should be noted that the base of the laneway was built using different materials in different sections, and I was told by participant 1 that this type of variable base placement was highly labour intensive.

We discussed that as city crews become more accustomed to the new construction methods required for Country Lane projects, and as designs are refined through lessons learned, Country Lanes with extruded driving strips could cost approximately 25% – 100% more than a traditional full width asphalt lane pave. If the city decided to forego the extruded concrete driving strips, and rather chose to include structural gravel drivable strips instead, the design and construction costs could be approximately 25% – 50% more than a traditional full width asphalt lane pave. We concluded our discussion on costs by stating that these specialized laneways are generally expected to cost a premium over asphalt lanes. This is because Country Lanes have more construction steps required, and during the construction process, labour costs increase because of the intensive and detailed hand work that is generally required.

Participant 1 stated that long term maintenance costs of these new laneways are also a concern for city staff. I was told that the City of Vancouver generally does not maintain its lanes, other than isolated asphalt patching when required. Country lanes however generally require significantly more frequent and labour intensive maintenance. Possible long term maintenance could include mowing the grassy areas, re-seeding grassy strips to ensure a thick grass cover, watering, weeding, and maintaining the planting areas, the driveway connections and laneway entrances. Other considerations include possible drainage issues associated with overland flow, costs incurred due to the cracking of the concrete driveable strips, and the deterioration of the structural grass product. More specifically, pine needles and leaves collecting within the cells of the structural grass can significantly reduce the infiltration capacity of the laneway by clogging these cells.

In the interview participant 1 told me that maintaining the structural grass was the city's biggest concern and if the structural grass were to fail, the city could be responsible for costly repairs. We discussed that isolated structural grass repairs are not as cost effective as traditional asphalt patching because replacing individual structural grass panels can be difficult, time consuming, and labour intensive.

Beside the construction concerns listed above, I was told that routine maintenance such as mowing, and watering also needed to be considered. Participant 1 and I discussed that cities can shift these highly repetitive maintenance obligations onto the residents that use these specialized laneways; however, it was noted that this approach may not be appropriate in some communities where residents are not motivated or dedicated to maintaining their rear laneways. This raises an important question of who should be tasked with providing long term maintenance: the city or the residents? We discussed that in cases where residents are motivated to undertake routine maintenance, these tasks should be left to the community, and city staff should monitor the laneways to ensure that the grass is mowed, and the plants are watered. City staff should inspect these laneway areas regularly since inadequate maintenance could alter the permeability of the lane which can result in drainage failures. In situations where residents are not willing to undertake any maintenance obligations, participant 1 suggested that municipalities look for alternative locations to construct Country Lanes, preferably in areas with active and involved communities. Alternatively, if the city wanted to take on all maintenance requirements, additional funding and staffing resources may need to be considered.

5.3.4. Sanitation Department Concerns with Country Lanes

Participant 1 told me that before designs were undertaken, city staff consulted with their sanitation department, and while staff were supportive of a Country Lane design, many sanitation officers had specific concerns. First, staff were concerned about potential trip hazards forming in the rear laneway between the drivable strips and the surrounding softer permeable areas. They felt that over time, with enough vehicle traffic, different levels of settlement could occur within the laneway, and this could create trip hazards for solid waste and recycling staff. Second, I was told that sanitation staff were concerned about garbage trucks leaking on the grassy areas within the lane. Finally, I was told that all solid waste and recycling staff were concerned about passing vehicles within the rear laneways. I was informed that when city garbage or recycling truck drivers encounter another vehicle on a Country Lane, drivers are told to leave the driving strips, and pass the approaching vehicle. Generally, average sized garbage trucks weigh approximately 25 tonnes, and when these heavy vehicles drive off the drivable strips, this can create loading issues and damage to the surrounding softer edge materials.

In response to the loading concern above, participant 1 recommended that cities consider implementing one way traffic within Country Lanes where appropriate. This can be achieved through signage within the laneway, a one way traffic sign at the lane entrance, and a no entry sign at the lane exit. Given the concerns associated with maintaining structural grass within these specialized laneways, I was told that truck drivers should not be encouraged to drive over these softer surfaces. Creating one-way lanes with appropriate signage could be a reasonable solution to address this problem in some rear laneways.

5.3.5. Country Lanes and Post Construction Resident Feedback Questionnaire

Once all three Country Lanes were constructed as part of the city’s Demonstration Project, city staff distributed questionnaires to residents in the area. The feedback received was generally positive, and of the 21 questionnaires returned, only one resident was unhappy with the new Country Lane design (Helmus, 2004, p. 25). Prior to construction, participant 1 told me that most rear lanes had gravel surfaces, and many residents commented that some of the main benefits of the new Country Lanes were noise reduction, dust reduction, temperature reduction, the addition of aesthetically pleasing green space, and better rain absorption so no pooling or standing water accumulates within the lane. I was also told that the majority of respondents also believed that the new Country Lanes promoted traffic calming, and many residents noticed that vehicles were now travelling at lower speeds, which served to make the laneways safer.

The main concerns raised on the questionnaire were in response to poor grass growth within the new rear laneways. Some residents believed that the city needed to provide more maintenance services, and a few residents stated that they were disappointed with the lack of input they had with the initial lane designs. One of the final questions in the questionnaire asked residents if they would be prepared to pay an additional 50% cost premium to build a Country Lane, rather than a full-width asphalt lane in their neighbourhood. Of the 21 respondents, 11 (52%) of residents stated that they would pay the premium costs, 3 (14%) said that they would not pay this premium, and 7 (33%) of residents were undecided (Helmus, 2004, p. 25). Although only 21 responses were received by city staff, these results could suggest that while many residents may be in favour of Country Lanes, some may not be prepared to pay a cost premium to secure this sustainable laneway design.

Chapter 6. Conclusions

This thesis has highlighted the importance of sustainable stormwater management in cities. As discussed in Chapter 4, one of the leaders in innovation for green infrastructure solutions is the City of Philadelphia. Using our conceptual framework developed in the Literature Review section of this thesis, The District of North Vancouver and other municipalities can draw lessons from the City of Philadelphia's successes because of the following reasons. When it comes to determining the desirability of City of Philadelphia's green streets design manual, the programme in question is desirable and this is evidenced by the National Planning Award that the city received from the American Planning Association in 2015. The City of Vancouver's 2020 Greenest City Action Plan also notes that Vancouverites have historically made environmentally conscious choices. This is evidenced by the 1990 Clouds of Change Task Force that recommended the city begin reducing its carbon dioxide emissions and in doing so Vancouver became one of the first cities in the world to acknowledge the issue of climate change, and currently Vancouver has the smallest per capita carbon footprint in North America (CIty of Vancouver, 2020, p. 7). This demonstrates that the values of the citizens in Metro Vancouver aligns with the goals of sustainable stormwater solutions, which is to ensure a sustainable and livable community and planet. This also demonstrates that the programme is desirable as it was defined in my conceptual framework, since it aligns with the values of the residents within the recipient location.

When evaluating the practicality or technical feasibility of the programme all interview participants included within this study were aware of the City of Philadelphia's Green Street Design Manual, and this demonstrates the awareness that this relatively new technical design manual has received. More specifically, participants 1 and 3, who are both professional engineers, commented that this design manual was very technically thorough and did not simply prioritize stormwater management over the functionality or usability of roads or corridors. They noted that the green infrastructure solutions suggested within the manual are designed to both manage urban runoff while simultaneously considering the walkability, usability, and the aesthetic appeal of the street. As noted in my conceptual framework, technical feasibility can be challenging if based on abstract theories of social science, but is achievable when based on proven concepts such as engineering and environmental sciences. Therefore, similarly to how a car motor can be exported and customized to any jurisdiction, the engineered sustainable stormwater management solutions contained within the City of Philadelphia's Green Streets Design Manual can be exported to other jurisdictions such as the District of North Vancouver. This also demonstrates the reliability of the information contained within the manual, as the contents of the manual are engineered solutions that have also been evaluated and assessed by independent professional engineers interviewed within this study.

The next factor in determining whether a programme can be successfully transferred from one jurisdiction to another is to determine whether resources are available within the recipient jurisdictions. As discussed in Section 5.1.3 of this thesis, I highlighted the importance of sufficient staffing when implementing new programmes. In order to successfully draw lessons from other jurisdictions, there needs to be sufficient staffing to perform the necessary research and analysis of the information from the donor programme. Since some municipalities may require additional staffing resources within their engineering departments to complete this research, staff could be hired on a contractual basis to protect the municipality from overstaffing once this analysis is complete.

The last step of my conceptual framework is to evaluate if any constraints exist that could result in failure of policy transfer or lesson-drawing. The primary goal of sustainable stormwater management solutions as discussed in this thesis is environmental protection. This addresses the constraint of multiple goals being less likely to be transferred to a recipient jurisdiction as discussed in Section 2.3 of the Literature Review. The primary goal of sustainable stormwater management solutions aligns with the primary goal of the City of Philadelphia's Green Streets Design Manual, which is environmental sustainability.

Another constraint identified in Section 2.3 of the Literature review is whether problems with the existing policy can be easily remedied. While managing stormwater sustainably can be complicated from a technical standpoint, the City of Philadelphia has developed and successfully implemented a prescriptive and award winning design manual to address gaps within existing stormwater management policies. Another constraint discussed in the Literature Review notes that if there is a lack of relationship between the problem and the solution, then there could be a failure to transfer policy or draw lessons successfully. As discussed in this thesis, there is a direct relationship between improperly managed stormwater and pollution within receiving bodies of water, therefore jurisdictions looking to address this problem can look to the City of Philadelphia's Green Streets Design Manual to manage runoff more sustainably.

In evaluating whether we can successfully transfer policy from the City of Philadelphia to the District of North Vancouver, there needs to be an assessment of whether any potential side effects of the policy exists. As discussed in Section 2.4 of the Literature Review, vocal opposition to any new policy proposal can derail implementation. As discussed in Section 5.1.2 of this thesis, interview participant 3 noted that there could be initial opposition from the single-family development community due to the increased costs associated with implementing sustainable stormwater management solutions on all newly built single-family lots. Section 5.1.2 also discusses that this opposition could be reduced if municipalities draw lessons from the City of Victoria and choose to implement a stormwater user fee based on an impervious area calculation method. This could incentivise developers to build lots that manage runoff more sustainably, as this would likely attract future homebuyers to purchase these lots and pay lower stormwater user fees.

Finally, there needs to be an assessment of how easily outcomes from implementing green infrastructure and low impact development solutions can be predicted. In order to do this, the District of North Vancouver and other recipient jurisdictions could hire independent engineering consulting firms to prepare forecasts and models of pollution levels after sustainable stormwater management solutions have been implemented.

This thesis has emphasised the importance of stormwater management in cities. The extensive background, and technical sustainable stormwater management solutions cited within this study were included in an effort to highlight the importance of this issue and provide sustainable alternatives to supplement conventional stormwater management techniques. As discussed in Chapter 1 and Chapter 5, as cities continue to densify, and as populations continue to grow, municipalities generally tend to notice a reduction of permeable surfaces within urbanized areas. Planners, engineers, and other civil designers often alter naturalized areas by building roads, structures, and other amenities required for the cities to function appropriately. In many cases, the development process results in considerable alteration of the land in comparison with pre-developmental conditions, and significantly less rainwater is able to infiltrate back into the ground. Managing surface water as it travels over hard impervious lands, picking up pollutants can be challenging. Watershed managers need to be able to predict the amount of rainfall expected within their areas; however, climate change can complicate matters due to unexpected changes in the intensity, duration, and frequency of rain events. In certain cities, climate change can create significant storm events, which can lead to flooding, erosion, property damage, and pollution problems in downstream receiving areas if stormwater is not managed sustainably. In other cities around the world, climate change can contribute to droughts, and water conservation strategies may be necessary in order to safeguard a city's potable water supply. Helping the public understand the potential problems associated with mismanaging stormwater is often necessary, and as discussed in Section 4.9, the City of Philadelphia attributed the success of the implementation of their programme to educating and engaging the public.

During the interview process, participant 6 told me that in many wealthy, developed cities around the world, stormwater management is rarely considered by members of the public because if flooding is not experienced, the public is generally not affected. In cities like Vancouver, citizens generally expect city streets to be clean, and free of puddles or standing water. Significant flooding is fairly infrequent, however, what many members of the public do not understand is how stormwater is managed in order to achieve this expectation. It is important to be reminded about the problems that improperly managed stormwater can have on downstream receiving environments. Losses in biodiversity, the degradation of aquatic health, the deterioration of salmon populations, pollution, erosion, and property damage are some of the more common problems associated with improperly managing stormwater.

As discussed throughout the thesis, conventionally managing stormwater through pipes alone does not appear to be a sustainable solution, especially in cities that still use combined sewers to convey both sanitary water and stormwater within the same piped system. In an effort to address this issue, the research included within this thesis encourages readers to consider managing stormwater more naturally, and close to the source, by using green infrastructure and low impact development solutions that allow water to infiltrate back into the ground. While it is recognized that some of these solutions may be less cost effective, or may require more frequent maintenance, it is important to understand unmanaged stormwater can create negative consequences such as pollution and erosion in downstream receiving areas. Third party incentivization programs such as Salmon Safe BC are currently working on certifying sites as Salmon Safe in an effort to promote sustainable stormwater management solutions and safeguard the health of salmon populations. These types of incentivization programs can be beneficial in protecting our environment by promoting more natural ways to manage stormwater sustainably.

Within Chapter 4 of this thesis, I have cited several green infrastructure and low impact development solutions that can be considered and used within the urban environment. Understanding that spatial constraints can be problematic in urban areas, Chapter 4 of this thesis has cited several natural stormwater management solutions that can be used on spatially constrained sites, or within spatially constrained areas of the city. Single storm trees for example can be considered in areas where space is limited, and storm tree trenches can be implemented in larger, more open areas around the city. Benefits and considerations for each solution have also been cited within Chapter 4. Performance measures and more extensive technical details were also included for bio swales, porous asphalt surfaces, and green roof systems because these low impact development strategies are more commonly used today, and because these strategies have been studied and well documented by researchers. Other technologies are newer and are still being studied and evaluated by researchers today.

As discussed in Chapter 5, municipalities can instill a lot of change within a city if staff are able to secure sustainable stormwater management solutions on all newly developed lots; however, securing these solutions can be difficult in the absence of clear bylaw and policy requirements. As a policy recommendation, this thesis discusses that cities should consider implementing a stormwater user fee as a dedicated source of funding for stormwater management programmes. As discussed in Section 4.9.2 of this thesis, a stormwater user fee can be understood as a “user pay” fee, and drawing lessons from the City of Victoria, stormwater user fees should ideally be implemented based on impervious area calculations. If structured in this way, stormwater user fees can help cover the costs of stormwater management in a city, while also incentivizing developers and landowners to build sites that manage runoff more sustainably. Additionally, stormwater user fees can be charged based on a fair allocation of benefits and costs so that the total fees collected could make the utility self-sufficient so that little or no subsidy is required from the property tax base. As noted earlier in this conclusion, the residents of Metro Vancouver have a propensity for environmental sustainability. A stormwater user fee is a policy instrument intended to aid in the implementation of sustainable solutions for stormwater management. The goal of managing stormwater runoff sustainably is to ensure a reduction of pollution in receiving bodies of water for a greener and more sustainable planet. Since this policy instrument represents a vision for change in how we manage pollution in runoff, this could be used as a rationale to enable citizens and their representatives on council to pass legislation in favor of these stormwater user fees.

Within the limits of private property, as discussed by the interview participants in Chapter 5, cities *should* focus their attention on securing sustainable stormwater management solutions on both newly constructed single-family, and non-single family lots. On public land, cities can consider permeable country lane designs in appropriate rear laneways, but before any changes can be made, public consultation is important. As discussed in Section 5.3.3, since country lanes require routine maintenance, city staff should consider these specialized lane designs primarily in areas where residents understand the drainage and aesthetic benefits of the final product, and are willing to maintain the lanes that they use. As highlighted by participant 1 in Section 5.3.4, country Lanes should also be limited to one way traffic only given the maintenance problems and costs associated with repairing the structural grass.

The literature reviewed in Chapter 2 on policy transfer and lesson-drawing highlights that the problems faced by jurisdictions are not unique, and the sustainable management of stormwater in cities is no exception. As cities continue to grow and as permeable surfaces continue to be replaced with impermeable surfaces, less rainwater is able to infiltrate back into the ground. As this water travels over land, it picks up toxic pollutants and needs to be managed appropriately. Since this is not a unique occurrence, lessons can be drawn from municipalities such as the City of Philadelphia who have successfully implemented recognized programmes to manage stormwater runoff more sustainably.

References

Abustan, I., Hamzah, M. O., & Rashid, M. A. (2012). *Review of Permeable Pavement Systems in Malaysia Conditions*. 10.

Ahiablame, L. M., Engel, B. A., & Chaubey, I. (2012). Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research. *Water, Air, & Soil Pollution*, *223*(7), 4253–4273. https://doi.org/10.1007/s11270-012-1189-2

American Planning Association. (2015). *Green City, Clean Waters: Philadelphia's 21st Century Green Stormwater Infrastructure Program*. American Planning Association. Retrieved August 9, 2020, from https://www.planning.org/awards/2015/greencity.htm

Antunes, L., Thives, L., & Ghisi, E. (2016). Potential for Potable Water Savings in Buildings by Using Stormwater Harvested from Porous Pavements. *Water*, *8*(4), 110. https://doi.org/10.3390/w8040110

Askarizadeh, A., Rippy, M. A., Fletcher, T. D., Feldman, D. L., Peng, J., Bowler, P., Mehring, A. S., Winfrey, B. K., Vrugt, J. A., AghaKouchak, A., Jiang, S. C., Sanders, B. F., Levin, L. A., Taylor, S., & Grant, S. B. (2015). From Rain Tanks to Catchments: Use of Low-Impact Development To Address Hydrologic Symptoms of the Urban Stream Syndrome. *Environmental Science & Technology*, *49*(19), 11264–11280. https://doi.org/10.1021/acs.est.5b01635

Backhaus, A., & Fryd, O. (2013). The aesthetic performance of urban landscape-based stormwater management systems: A review of twenty projects in Northern Europe. *Journal of Landscape Architecture*, *8*(2), 52–63. https://doi.org/10.1080/18626033.2013.864130

Bardgett, R. D., Mommer, L., & De Vries, F. T. (2014). Going underground: Root traits as drivers of ecosystem processes. *Trends in Ecology & Evolution*, *29*(12), 692–699. https://doi.org/10.1016/j.tree.2014.10.006

Barrett Michael E., Irish Lyn B., Malina Joseph F., & Charbeneau Randall J. (1998). Characterization of Highway Runoff in Austin, Texas, Area. *Journal of Environmental Engineering*, *124*(2), 131–137. https://doi.org/10.1061/(ASCE)0733-9372(1998)124:2(131)

Beecham, S., & Myers, B. (2007). Structural and Design Aspects of Porous and Permeable Block Pavement. *J. Aust. Ceram. Soc.*, *43*.

Bennett, C. J., & Howlett, M. (1992). The lessons of learning: Reconciling theories of policy learning and policy change. *Policy Sciences*, *25*(3), 275–294. https://doi.org/10.1007/BF00138786

Berbee, R., Rijs, G., de Brouwer, R., & van Velzen, L. (1999). Characterization and Treatment of Runoff from Highways in the Netherlands Paved with Impervious and Pervious Asphalt. *Water Environment Research*, *71*(2), 183–190. JSTOR.

Bredemeier, M. (Ed.). (2011). *Forest management and the water cycle*. Springer.

Brinker, S. R., Garvey, M., & Jones, C. D. (2018). *Climate change vulnerability assessment of species in the Ontario Great Lakes Basin*. 190.

Brudler, S., Arnbjerg-Nielsen, K., Hauschild, M. Z., & Rygaard, M. (2016). Life cycle assessment of stormwater management in the context of climate change adaptation. *Water Research*, *106*, 394–404. https://doi.org/10.1016/j.watres.2016.10.024

Canadian Business for Social Responsibility. (2015). *MEC Headquarters Certified as BC's First Salmon-Safe Urban Site*. Retrieved February 23, 2020, from http://cbsr.ca/2015/11/19/mec-headquarters-certified-as-bcs-first-salmon-safe-urban-site/

Centre of Disease Control and Prevention. (2018). *Global WASH Fast Facts | Global Water, Sanitation and Hygiene | Healthy Water | CDC*. Retrieved February 23, 2020, from https://www.cdc.gov/healthywater/global/wash_statistics.html

Chai Lin, Kayhanian Masoud, Givens Brandon, Harvey John T., & Jones David. (2012). Hydraulic Performance of Fully Permeable Highway Shoulder for Storm Water Runoff Management. *Journal of Environmental Engineering*, *138*(7), 711–722. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000523

Chandrasena, G. I., Deletic, A., & McCarthy, D. T. (2014). Survival of Escherichia coli in stormwater biofilters. *Environmental Science and Pollution Research*, *21*(8), 5391–5401. https://doi.org/10.1007/s11356-013-2430-2

Chang, N.-B., Lu, J.-W., Chui, T. F. M., & Hartshorn, N. (2018). Global policy analysis of low impact development for stormwater management in urban regions. *Land Use Policy*, *70*, 368–383. https://doi.org/10.1016/j.landusepol.2017.11.024

Chughtai, M., Mustafa, S., & Mumtaz, M. (2014). Study of Physicochemical Parameters of Rainwater: A Case Study of Karachi, Pakistan. *American Journal of Analytical Chemistry*, *05*(04), 235–242. https://doi.org/10.4236/ajac.2014.54029

City of Guelph. (2014). *City of Guelph: Streetscape Manual* (p. 130) [Design Manual]. http://guelph.ca/wp-content/uploads/Section_2_Streetscape_ManualREVISEdJAN20172Reduced.pdf

City of Philadelphia. (2014). *City of Philadelphia Green Streets Design Manual* (p. 95) [Design Manual]. http://www.mapc.org/wp-content/uploads/2017/10/GSDM_FINAL_20140211.pdf

City of Toronto. (2017). *Wastewater Treatment Plant Bypasses*. City of Toronto. Retrieved November 20, 2019, from https://www.toronto.ca/services-payments/water-environment/managing-sewage-in-toronto/wastewater-treatment-plant-bypasses/

City of Vancouver. (2002). *Country Lanes Demonstration Project* (p. 7). https://council.vancouver.ca/020709/A5.htm

City of Vancouver. (2016). *COV Integrated Rainwater Management Plan* (p. 69). https://vancouver.ca/files/cov/integrated-stormwater-management-vision-principles-and-actions-volume-1.pdf

City of Vancouver. (2019). *Separating Sewage From Rainwater*. Retrieved November 17, 2019, from https://vancouver.ca/home-property-development/separating-sewage-from-rainwater.aspx

CIty of Vancouver. (2020). *Greenest City Action Plan* (p. 82).

City of Victoria. (2016). *Stormwater Utility*. Https://Www.Victoria.Ca.Retrieved August 1, 2020, from https://www.victoria.ca/EN/main/residents/water-sewer-stormwater/stormwater/stormwater-utility.html

Coleri, E., Kayhanian, M., Harvey, J. T., Yang, K., & Boone, J. M. (2013). Clogging evaluation of open graded friction course pavements tested under rainfall and heavy vehicle simulators. *Journal of Environmental Management*, *129*, 164–172. https://doi.org/10.1016/j.jenvman.2013.07.005

Dechesne, M., Barraud, S., & Bardin, J.-P. (2004). Indicators for hydraulic and pollution retention assessment of stormwater infiltration basins. *Journal of Environmental Management*, *71*(4), 371–380. https://doi.org/10.1016/j.jenvman.2004.04.005

Delleur, J. (2003). *The evolution of urban hydrology: Past, present, and future*. 563–573.

Denault, C., Millar, R., & Lence, B. (2002). *Climate Change and Drainage Infrastructure Capacity in an Urban Catchment. Proceedings, Annual Conference—Canadian Society for Civil Engineering.* https://www.researchgate.net/publication/253462402_Climate_Change_and_Drainage_Infrastructure_Capacity_in_an_Urban_Catchment

Dhakal, K. P., & Chevalier, L. R. (2016). Urban Stormwater Governance: The Need for a Paradigm Shift. *Environmental Management*, *57*(5), 1112–1124. https://doi.org/10.1007/s00267-016-0667-5

District of North Vancouver. (2019). *Integrated Stormwater Management Plan*. District of North Vancouver. Retrieved June 25, 2019, from https://www.dnv.org/programs-and-services/integrated-stormwater-management-plan

Dolowitz, D., & Marsh, D. (1996). *Who Learns What From Whom*. 343–357.

Eckart, K., McPhee, Z., & Bolisetti, T. (2017). Performance and implementation of low impact development – A review. *Science of The Total Environment*, *607–608*, 413–432. https://doi.org/10.1016/j.scitotenv.2017.06.254

Ecological Society of America. (2015). *Managing Stormwater to Save Salmon*. *13*, 1.

Egodawatta, P., Thomas, E., & Goonetilleke, A. (2009). Understanding the physical processes of pollutant build-up and wash-off on roof surfaces. *Science of The Total Environment*, *407*(6), 1834–1841. https://doi.org/10.1016/j.scitotenv.2008.12.027

Environmental Commissioner of Ontario. (2016). *Read—Urban Stormwater Fees: How to Pay for What We Need: Environmental Commissioner of Ontario—DesLibris*. Retrieved February 9, 2020, from https://www-deslibris-ca.proxy.lib.sfu.ca/ID/10064235

Environmental Law Clinic. (2010). *Re-Inventing Rainwater Management* (p. 101). https://www.waterbucket.ca/rm/sites/wbcrm/documents/media/118.pdf

Evans, M. (2006). At The Interface Between Throry and Practice—Policy Transfer and Lesson-Drawing. *Public Administration*, *84*(2), 479–489. https://doi.org/10.1111/j.1467-9299.2006.00013.x

Evans, M., & Davies, J. (1999). Understanding Policy Transfer: A Multi-Level, Multi-Disciplinary Perspective. *Public Administration*, *77*(2), 361–385. https://doi.org/10.1111/1467-9299.00158

Fitzgerald, J., & Laufer, J. (2017). Governing green stormwater infrastructure: The Philadelphia experience. *Local Environment*, *22*(2), 256–268. https://doi.org/10.1080/13549839.2016.1191063

Fraser Basin Council. (2019). *Fraser Basin Council—Salmon-Safe BC*. Fraser Basin Council. Retrieved November 23, 2019, from https://www.fraserbasin.bc.ca/water_salmon-safe.html

Gaffield, S. J., Goo, R. L., Richards, L. A., & Jackson, R. J. (2003). Public Health Effects of Inadequately Managed Stormwater Runoff. *American Journal of Public Health*, *93*(9), 1527–1533. https://doi.org/10.2105/AJPH.93.9.1527

Gaffin, S. R., Rosenzweig, C., & Kong, A. Y. Y. (2012). Adapting to climate change through urban green infrastructure. *Nature Climate Change*, *2*(10), 704–704. https://doi.org/10.1038/nclimate1685

Giuliani, F., Autelitano, F., Degiovanni, E., & Montepara, A. (2017). DEM modelling analysis of tree root growth in street pavements. *International Journal of Pavement Engineering*, *18*(1), 1–10. https://doi.org/10.1080/10298436.2015.1019495

Government of Canada, E. and C. C. (2018, September 26). *Changes in temperature*. Aem. Retrieved August 8, 2020, from https://www.canada.ca/en/environment-climate-change/services/climate-change/canadian-centre-climate-services/basics/trends-projections/changes-temperature.html

Grant, S. B., Saphores, J.-D., Feldman, D. L., Hamilton, A. J., Fletcher, T. D., Cook, P. L. M., Stewardson, M., Sanders, B. F., Levin, L. A., Ambrose, R. F., Deletic, A., Brown, R., Jiang, S. C., Rosso, D., Cooper, W. J., & Marusic, I. (2012). Taking the “Waste” Out of “Wastewater” for Human Water Security and Ecosystem Sustainability. *Science*, *337*(6095), 681–686. https://doi.org/10.1126/science.1216852

Greater Vancouver Sewerage and Drainage District. (2018). *Study of the Impacts of Climate Change on Precipitation and Stormwater Management* (p. 133). http://www.metrovancouver.org/services/liquid-waste/LiquidWastePublications/TMs-GHD-StudyImpacts-ClimateChangePrecipitationStormwater-2018.pdf

Grebel, J. E., Mohanty, S. K., Torkelson, A. A., Boehm, A. B., Higgins, C. P., Maxwell, R. M., Nelson, K. L., & Sedlak, D. L. (2013). Engineered Infiltration Systems for Urban Stormwater Reclamation. *Environmental Engineering Science*, *30*(8), 437–454. https://doi.org/10.1089/ees.2012.0312

Gromaire, M. C., Robert-Sainte, P., Bressy, A., Saad, M., De Gouvello, B., & Chebbo, G. (2011). Zn and Pb emissions from roofing materials – modelling and mass balance attempt at the scale of a small urban catchment. *Water Science and Technology*, *63*(11), 2590–2597. https://doi.org/10.2166/wst.2011.160

Haley, D., & Auld, H. (2000). *Integration of Climate Change Into Watershed Management*. 14.

Hammes, G., Thives, L. P., & Ghisi, E. (2018). Application of stormwater collected from porous asphalt pavements for non-potable uses in buildings. *Journal of Environmental Management*, *222*, 338–347. https://doi.org/10.1016/j.jenvman.2018.05.094

Hamzah, M. O., Z.F.M, J., & Fauziah, A. (2012). *Laboratory Assessment of Water Flow Simulator for Porous Parking Lots System*. World Appl. Sci. J. 16, 748–758 ISSN 1818-4952. https://doi.org/10.3923/jas.2011.3464.3473

Hansen, K. (2008). *Porous Asphalt Pavements for Sormwater Management* (p. 30) [Design, Construction, and Maintenance Guide]. National Asphalt Pavement Association (NAPA). http://driveasphalt.org/assets/content/resources/IS-131_Porous_Asphalt_Pavements_for_Sormwater_Management-screen.pdf

Helmus, J. (2004). *Ciy of Vancouver: Country Lanes* (p. 36) [Information Report].

Herngren, L., Goonetilleke, A., & Ayoko, G. A. (2005). Understanding heavy metal and suspended solids relationships in urban stormwater using simulated rainfall.

Journal of Environmental Management, *76*(2), 149–158. https://doi.org/10.1016/j.jenvman.2005.01.013

Horton, R., Rosenzweig, C., Gornitz, V., Bader, D., & O'Grady, M. (2010). CLIMATE RISK INFORMATION: Climate Change Scenarios & Implications for NYC Infrastructure New York City Panel on Climate Change. *Annals of the New York Academy of Sciences*, *1196*(1), 147–228. https://doi.org/10.1111/j.1749-6632.2010.05323.x

Howlett, M., Ramesh, M., & Perl, A. (2009). *Studying Public Policy: Policy Cycles & Policy Subsystems* (Third Edition). Oxford University press.

Hoyt, L. (2006). Importing Ideas: The Transnational Transfer of Urban Revitalization Policy. *International Journal of Public Administration*, *29*(1–3), 221–243. https://doi.org/10.1080/01900690500409096

Jackisch, N., & Weiler, M. (2017). The hydrologic outcome of a Low Impact Development (LID) site including superposition with streamflow peaks. *Urban Water Journal*, *14*(2), 143–159. https://doi.org/10.1080/1573062X.2015.1080735

Jacobson, C. R. (2011a). Identification and quantification of the hydrological impacts of imperviousness in urban catchments: A review. *Journal of Environmental Management*, *92*(6), 1438–1448. https://doi.org/10.1016/j.jenvman.2011.01.018

Jacobson, C. R. (2011b). Identification and quantification of the hydrological impacts of imperviousness in urban catchments: A review. *Journal of Environmental Management*, *92*(6), 1438–1448. https://doi.org/10.1016/j.jenvman.2011.01.018

James, W., & von Landsdorff, H. (2003). The Use of Permeable Concrete Block Pavement in Controlling Environmental Stressors in Urban Areas. *In: Proceedings of the 7th International Conference on Concrete Block Paving (PAVE AFRICA 2003)*, 11.

Johns, C. M. (2019). Understanding barriers to green infrastructure policy and stormwater management in the City of Toronto: A shift from grey to green or policy layering and conversion? *Journal of Environmental Planning and Management*, *62*(8), 1377–1401. https://doi.org/10.1080/09640568.2018.1496072

Kayhanian, M., Vichare, A., Green, P. G., & Harvey, J. (2009). Leachability of dissolved chromium in asphalt and concrete surfacing materials. *Journal of Environmental Management*, *90*(11), 3574–3580. https://doi.org/10.1016/j.jenvman.2009.06.011

Kim, M. H., Sung, C. Y., Li, M. B., & Chu, K. H. (2012). *Bioretention for stormwater quality improvement in Texas: Removal effectiveness of Escherichia coli*. https://doi.org/10.1016/j.seppur.2011.04.025

Kuliczkowska, E., & Parka, A. (2017). Management of risk of tree and shrub root intrusion into sewers. *Urban Forestry & Urban Greening*, *21*, 1–10. https://doi.org/10.1016/j.ufug.2016.11.001

Kwiatkowski, M., Welker, A. L., Traver, R. G., Vanacore, M., & Ladd, T. (2007). Evaluation of an Infiltration Best Management Practice Utilizing Pervious Concrete. *Journal of the American Water Resources Association*, *43*(5), 1208–1222. https://doi.org/10.1111/j.1752-1688.2007.00104.x

Le Coustumer, S., Fletcher, T. D., Deletic, A., & Barraud, S. (2007). Hydraulic performance of biofilters for stormwater management: First lessons from both laboratory and field studies. *Water Science and Technology*, *56*(10), 93–100. https://doi.org/10.2166/wst.2007.735

Legret, M., & Colandini, V. (1999). Effects of a porous pavement with reservoir structure on runoff water: Water quality and fate of heavy metals. *Water Science and Technology*, *39*(2), 111–117. https://doi.org/10.2166/wst.1999.0098

Li, Y. L., Deletic, A., Alcazar, L., Bratieres, K., Fletcher, T. D., & McCarthy, D. T. (2012). Removal of Clostridium perfringens, Escherichia coli and F-RNA coliphages by stormwater biofilters. *Ecological Engineering*, *49*, 137–145. https://doi.org/10.1016/j.ecoleng.2012.08.007

Lieberherr, E., & Green, O. (2018). Green Infrastructure through Citizen Stormwater Management: Policy Instruments, Participation and Engagement. *Sustainability*, *10*(6), 2099. https://doi.org/10.3390/su10062099

Madoux-Humery, A.-S., Dorner, S., Sauvé, S., Aboulfadl, K., Galarneau, M., Servais, P., & Prévost, M. (2013). Temporal variability of combined sewer overflow contaminants: Evaluation of wastewater micropollutants as tracers of fecal contamination. *Water Research*, *47*(13), 4370–4382. https://doi.org/10.1016/j.watres.2013.04.030

May, P. J. (1992). *Policy Learning and Failure*. 25.

McIntyre, J. K., Lundin, J. I., Cameron, J. R., Chow, M. I., Davis, J. W., Incardona, J. P., & Scholz, N. L. (2018). Interspecies variation in the susceptibility of adult Pacific salmon to toxic urban stormwater runoff. *Environmental Pollution*, *238*, 196–203. https://doi.org/10.1016/j.envpol.2018.03.012

McKinnon, D., & Posedowski, B. (2014). *Accelerated Remediation of Illegal Sewer Cross Connections* (p. 8) [Council Report]. http://hamiltonharbour.ca/resources/documents/SewerCross-ConnectionPilotStudyreport,publicworkscommittee.pdf

McLellan, S. L., Hollis, E. J., Depas, M. M., Van Dyke, M., Harris, J., & Scopel, C. O. (2007). Distribution and Fate of Escherichia coli in Lake Michigan Following Contamination with Urban Stormwater and Combined Sewer Overflows. *Journal of Great Lakes Research*, *33*(3), 566. https://doi.org/10.3394/0380-1330(2007)33[566:DAFOEC]2.0.CO;2

Meenar, M. R. (2019). Integrating placemaking concepts into Green Stormwater Infrastructure design in the City of Philadelphia. *Environmental Practice*, *21*(1), 4–19. https://doi.org/10.1080/14660466.2019.1568121

Metro Vancouver. (2010). *Integrated Liquid Waste and Resource Management—A Liquid Waste Management Plan*. 38.

Metro Vancouver. (2019a). *A Homeowner's Guide to Stormwater Management* (p. 11).

Metro Vancouver. (2019b). *About Stormwater*. Retrieved July 9, 2020, from http://www.metrovancouver.org:80/services/liquid-waste/drainage/stormwater-management/about-stormwater/Pages/default.aspx

Miller, J. D., Kim, H., Kjeldsen, T. R., Packman, J., Grebby, S., & Dearden, R. (2014). Assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover. *Journal of Hydrology*, *515*, 59–70. https://doi.org/10.1016/j.jhydrol.2014.04.011

Moore, T. L., Gulliver, J. S., Stack, L., & Simpson, M. H. (2016). Stormwater Management and Climate Change: Vulnerability and Capacity for Adaptation In Urban and Suburban Contexts. *Climatic Change*, *138*(3–4), 491–504. https://doi.org/10.1007/s10584-016-1766-2

NASA. (2020). *The Causes of Climate Change*. Climate Change: Vital Signs of the Planet. Retrieved August 8, 2020, from https://climate.nasa.gov/causes

O'Neill, S., & Cairns, S. (2016). *New Solutions for Sustainable Stormwater Management in Canada* (p. 92). https://www-deslibris-ca.proxy.lib.sfu.ca/ID/10065516

Pacific Salmon Foundation. (2015). *MEC headquarters certified as BC's first Salmon-Safe urban site | Pacific Salmon Foundation*. Retrieved November 20, 2019, from https://www.psf.ca/news-media/mec-headquarters-certified-bc%E2%80%99s-first-salmon-safe-urban-site

Pagotto, C., Legret, M., & Le Cloirec, P. (2000). Comparison of the hydraulic behaviour and the quality of highway runoff water according to the type of pavement. *Water Research*, *34*(18), 4446–4454. https://doi.org/10.1016/S0043-1354(00)00221-9

Palla, A., Sansalone, J. J., Gnecco, I., & Lanza, L. G. (2011). Storm water infiltration in a monitored green roof for hydrologic restoration. *Water Science and Technology*, *64*(3), 766–773. https://doi.org/10.2166/wst.2011.171

Pendleton, L. (2008). The Economics of Using Ocean Observing Systems to Improve Beach Closure Policy. *Coastal Management*, *36*(2), 165–178. https://doi.org/10.1080/08920750701866352

Peng, J., Cao, Y., Rippy, M., Afrooz, A., & Grant, S. (2016). Indicator and Pathogen Removal by Low Impact Development Best Management Practices. *Water*, *8*(12), 600. https://doi.org/10.3390/w8120600

Petrucci, G., Rioust, E., Deroubaix, J.-F., & Tassin, B. (2013). Do stormwater source control policies deliver the right hydrologic outcomes? *Journal of Hydrology*, *485*, 188–200. https://doi.org/10.1016/j.jhydrol.2012.06.018

Pitt, R., Field, R., Lalor, M., & Brown, M. (1995). Urban stormwater toxic pollutants: Assessment, sources, and treatability. *Water Environment Research*, *67*(3), 260–275. https://doi.org/10.2175/106143095X131466

Podolsky, L., & MacDonald, E. (2008). *Green Cities, Great Lakes: Using Green Infrastructure to Reduce Combined Sewer Overflows*. Retrieved November 17, 2019, from https://www.deslibris.ca/ID/252966

Pratt, C. J. (1999). Use of permeable, reservoir pavement constructions for stormwater treatment and storage for re-use. *Water Science and Technology*, *39*(5), 145–151. https://doi.org/10.1016/S0273-1223(99)00096-7

Ramsay Worden Architects. (2015). *Lynn Valley Town Centre Public Realm and Design Guidelines*. https://www.dnv.org/sites/default/files/edocs/lynn-valley-design-guidelines.pdf

Randrup Thomas B., McPherson E. Gregory, & Costello Laurence R. (2001). Tree Root Intrusion in Sewer Systems: Review of Extent and Costs. *Journal of Infrastructure Systems*, *7*(1), 26–31. https://doi.org/10.1061/(ASCE)1076-0342(2001)7:1(26)

Rasmussen, T., & Schmidt, H. (2009). *Stormwater Runoff:What it is and why it is important in Johnson County, Kansas* (p. 2) [Fact Sheet]. https://permanent.access.gpo.gov/gpo2271/FS2009-3103.pdf

Read, J., Fletcher, T. D., Wevill, T., & Deletic, A. (2009). Plant Traits that Enhance Pollutant Removal from Stormwater in Biofiltration Systems. *International Journal of Phytoremediation*, *12*(1), 34–53. https://doi.org/10.1080/15226510902767114

Rippy, M. A. (2015). Meeting the criteria: Linking biofilter design to fecal indicator bacteria removal: Linking biofilter design to FIB removal. *Wiley Interdisciplinary Reviews: Water*, *2*(5), 577–592. https://doi.org/10.1002/wat2.1096

Rose, R. (1991). What is Lesson-Drawing? *Journal of Public Policy*, *11*(1), 3–30. https://doi.org/10.1017/S0143814X00004918

Roseen Robert M., Ballestero Thomas P., Houle James J., Briggs Joshua F., & Houle Kristopher M. (2012). Water Quality and Hydrologic Performance of a Porous Asphalt Pavement as a Storm-Water Treatment Strategy in a Cold Climate. *Journal of Environmental Engineering*, *138*(1), 81–89. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000459

Rosenberg, E. A., Keys, P. W., Booth, D. B., Hartley, D., Burkey, J., Steinemann, A. C., & Lettenmaier, D. P. (2010). Precipitation extremes and the impacts of climate change on stormwater infrastructure in Washington State. *Climatic Change*, *102*(1–2), 319–349. https://doi.org/10.1007/s10584-010-9847-0

Salmon Safe—Urban Site Certification Program. (2017). Diamond Head. Retrieved November 7, 2019, from http://www.diamondheadconsulting.com/blog/2017/2/21/salmon-safe-urban-site-certification-program

Santamouris, M. (2014). Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy*, *103*, 682–703. https://doi.org/10.1016/j.solener.2012.07.003

Schollen & Company, & Urban Forest Innovations. (2017). *Toronto Green Streets Technical Guide* (p. 50). https://www.toronto.ca/legdocs/mmis/2017/pw/bgrd/backgroundfile-107514.pdf

Scholz, M., & Grabowiecki, P. (2009). Combined permeable pavement and ground source heat pump systems to treat urban runoff. *Journal of Chemical Technology & Biotechnology*, *84*(3), 405–413. https://doi.org/10.1002/jctb.2054

Schooley, R. (1999). Vancouver Pipes a Source of Envy. *Journal of Commerce; Vancouver*, *88*(31), FS1-FS2+.

Schueler, T. R. (1987). *Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs*. Metropolitan Washington Council of Governments. file:///Users/kayzadnadirshaw/Desktop/Urban%20runoff%20pollution%20prevention%20and%20control%20planning%20-%20Google%20Books.htm

Shang, J., Flury, M., & Deng, Y. (2009). Force measurements between particles and the air-water interface: Implications for particle mobilization in unsaturated porous media: FORCES BETWEEN PARTICLES AND AIR-WATER INTERFACE. *Water Resources Research*, *45*(6). https://doi.org/10.1029/2008WR007384

Sohn, W., Kim, J.-H., & Li, M.-H. (2017). Low-impact development for impervious surface connectivity mitigation: Assessment of directly connected impervious areas (DCIAs). *Journal of Environmental Planning and Management*, *60*(10), 1871–1889. https://doi.org/10.1080/09640568.2016.1264929

Soller, J., Stephenson, J., Olivieri, K., Downing, J., & Olivieri, A. W. (2005). Evaluation of seasonal scale first flush pollutant loading and implications for urban runoff management. *Journal of Environmental Management*, *76*(4), 309–318. https://doi.org/10.1016/j.jenvman.2004.12.007

Stovin, V., Vesuviano, G., & Kasmin, H. (2012). The hydrological performance of a green roof test bed under UK climatic conditions. *Journal of Hydrology*, *414–415*, 148–161. https://doi.org/10.1016/j.jhydrol.2011.10.022

Sustainable Technologies. (2019). Swales and Roadside Ditches. *Sustainable Technologies Evaluation Program (STEP)*. Retrieved November 26, 2019, from https://sustainabletechnologies.ca/home/urban-runoff-green-infrastructure/low-impact-development/swales-and-roadside-ditches/

Takebayashi, H., & Moriyama, M. (2007). Surface heat budget on green roof and high reflection roof for mitigation of urban heat island. *Building and Environment*, *42*(8), 2971–2979. https://doi.org/10.1016/j.buildenv.2006.06.017

Tedoldi, D., Chebbo, G., Pierlot, D., Kovacs, Y., & Gromaire, M.-C. (2016). Impact of runoff infiltration on contaminant accumulation and transport in the soil/filter media of Sustainable Urban Drainage Systems: A literature review. *Science of The Total Environment*, *569–570*, 904–926. https://doi.org/10.1016/j.scitotenv.2016.04.215

The District of North Vancouver. (2017a). *District of North Vancouver—Council Workshop 2017* (p. 6).

The District of North Vancouver. (2017b). *DNV Climate Change Adaptation Strategy* (p. 70). https://www.dnv.org/sites/default/files/edocs/climate-change-adaptation-strategy.pdf

TRCA. (2010). *Low Impact Development Stormwater Management Planning and Design Guide* [Toronto and Region Conservation for the Living City]. https://cvc.ca/wp-content/uploads/2014/04/LID-SWM-Guide-v1.0_2010_1_no-appendices.pdf

Ubronas, B., & Jones, J. E. (2002). *Summary of emergent urban stormwater themes, linking stormwater BMP designs and performance to receiving water impact mitigation*. 1–8.

UNHSC. (2014). *University of New Hampshire Stormwater Center (UNHSC)*. 30.

Urban Green Infrastructure Guidelines. (2017a). *Ultra-Urban Green Infrastructure Guidelines (Green Gutters)* (p. 10). https://www.denvergov.org/content/dam/denvergov/Portals/705/documents/guidelines/ultra-urban-gi-green-gutter.pdf

Urban Green Infrastructure Guidelines. (2017b). *Urban Green Infrastructure Guidelines (Storm Bump-Outs)* (p. 15). https://www.denvergov.org/content/dam/denvergov/Portals/705/documents/guidelines/ultra-urban-gi-bumpout-stormwater-planter.pdf

Urban Systems. (2012). *Integrated Stormwater Management Plans—Lessons Learned to 2011* (p. 34).

USGS Science for a Changing World. (2019). *Rain and Precipitation*. USGS Science for a Changing World. Retrieved July 11, 2019, from https://www.usgs.gov/special-topic/water-science-school/science/rain-and-precipitation?qt-science_center_objects=0#qt-science_center_objects

Versini, P.-A., Ramier, D., Berthier, E., & de Gouvello, B. (2015). Assessment of the hydrological impacts of green roof: From building scale to basin scale. *Journal of Hydrology*, *524*, 562–575. https://doi.org/10.1016/j.jhydrol.2015.03.020

Voyde, E., Fassman, E., & Simcock, R. (2010). Hydrology of an extensive living roof under sub-tropical climate conditions in Auckland, New Zealand. *Journal of Hydrology*, *394*(3–4), 384–395. https://doi.org/10.1016/j.jhydrol.2010.09.013

Walsh, C. J., Fletcher, T. D., & Burns, M. J. (2012). Urban Stormwater Runoff: A New Class of Environmental Flow Problem. *PLOS ONE*, *7*(9), e45814. https://doi.org/10.1371/journal.pone.0045814

Waters, D., Watt, W. E., Marsalek, J., & Anderson, B. C. (2003). Adaptation of a Storm Drainage System to Accommodate Increased Rainfall Resulting from Climate Change. *Journal of Environmental Planning and Management*, *46*(5), 755–770. https://doi.org/10.1080/0964056032000138472

Wolman, H., & Page, E. (2002). Policy Transfer among Local Governments: An Information-Theory Approach. *Governance*, *15*(4), 477–501. https://doi.org/10.1111/1468-0491.00198

World Health Organization. (2019). *Drinking-water*. Drinking Water. Retrieved August 10, 2019, from https://www.who.int/news-room/fact-sheets/detail/drinking-water

Wright, I. J., Reich, P. B., Westoby, M., Ackerly, D. D., Baruch, Z., Bongers, F., Cavender-Bares, J., Chapin, T., Cornelissen, J. H. C., Diemer, M., Flexas, J., Garnier, E., Groom, P. K., Gulias, J., Hikosaka, K., Lamont, B. B., Lee, T., Lee, W., Lusk, C., … Villar, R. (2004). The worldwide leaf economics spectrum. *Nature*, *428*(6985), 821–827. https://doi.org/10.1038/nature02403

Xie, J., Wu, C., Li, H., & Chen, G. (2017). Study on Storm-Water Management of Grassed Swales and Permeable Pavement Based on SWMM. *Water*, *9*(11), 840. https://doi.org/10.3390/w9110840

Yousef, Y. A., Section, M. E. R. L. S. and C. S., & Engineering, U. of C. F. C. of. (1980). *Urban stormwater and combined sewer overflow impact on receiving water bodies: Proceedings of the national conference, Orlando, Florida November 26-28, 1979*. Municipal Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency.